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PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

PREPARED BY:

Science Applications International Corporation

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ATC	Authority to Construct
dB	Decibel Level - relative
dBA	Decibel Level - absolute
dd	Distance doubled
DOH	State of Hawaii Department of Health
EPA	United States Environmental Protection Agency
GRP	Geothermal Resources Permit
GTW	Geothermal Test Well
H_2S	Hydrogen Sulfide
HMP	Hydrologic Monitoring Plan
LERZ	Lower East Rift Zone
m	Meters
mm	Millimeters
MAQMP	Meteorologic and Air Quality Monitoring Plan
MMMD	Mean Maximum Mixing Depth
MW	Megawatt
MSL	Mean Sea Level
NAAQS	National Ambient Air Quality Standards
NBS	National Bureau of Standards
NMP	Noise Monitoring Plan
NWS	National Weather Service
PGV	Puna Geothermal Venture
PM	Particulate Matter
ppb	Parts per billion
ppm	Parts per million
ppmv	Parts per million volume
PSD	Prevention of Significant Deterioration
QA	Quality Assurance
QC	Quality Control
RH	Relative Humidity
SAAQS	State Ambient Air Quality Standards
SLM	Sound Level Meter
TSP	Total Suspended Particulates
YSI	Yellow Springs Instrument
ZAM	Zero Air Module

PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

EXECUTIVE SUMMARY

This Hydrologic Monitoring Program is being submitted as part of the requirements of the Geothermal Resource Permit Condition 10. The Program as submitted is in full compliance with this condition. It will document the hydrologic conditions in the shallow aquifer in existing wells that occur in the vicinity of the site and at a water supply well on the site prior to and over the duration of the project activities.

Scope

The scope of the plan provides for quarterly monitoring of water levels and appropriate chemical species from existing wells completed in the shallow aquifer in those areas downgradient of the project area, at the Green Lake water supply, and from two monitoring wells located within the project boundary completed within the shallow aquifer.

The proposed scope of the monitoring program will be to:

- Review and update the well data files for existing non-geothermal wells in the site vicinity,
- Identify the location of the two on-site monitoring wells,
- Determine the flow gradient in the site vicinity by completing two on-site and rehabilitating a third, nearby, monitoring well (GTW III).
- Document background conditions for selected wells by conducting the initial round of complete water level measurements and water sampling at all monitoring wells and water supply locations prior to beginning injection activities at the site, and,

- Implement the proposed monitoring program by conducting measurements on a quarterly basis thereafter.

Permit Conditions 11 and 13 are, in part, related to ground water, but, since they relate to potential upset conditions for the project, any necessary response actions go beyond monitoring routine activities at the site. They require, in the event of shallow ground water contamination being caused by the project construction or operation (Condition #11) or the Green Lake Water Supply becoming contaminated as a result of the project (Condition #13), that the source of the contamination be eliminated and that an alternative water supply for Green Lake be provided.

PGV will immediately notify the County Planning Department and State Department of Health in situations when a change in geothermal well conditions indicates there is a leak or failure in the production or injection well casing. PGV will take the appropriate steps to test the production/injection system and evaluate the related well and casing downhole conditions. If leakage of geothermal waters to the shallow aquifer is demonstrated, any wells leaking would be shut in accordance with GRP Condition 11, and an assessment of the potential impact would be made by the monitoring contractor. In addition, steps would be identified to evaluate the impact as it relates to downgradient water users.

Equipment, Data Collection and Reporting

Water level meters will be used to measure the depth to water at all monitoring locations. Samples will be taken using pumps in wells equipped with these devices or using bailers. Field analyses will be supplemented by laboratory analyses for components that have been developed by PGV in concert with the State Department of Health, Safe Drinking Water Branch. All samples will be taken and field analyses conducted in accordance with standard protocols approved by the EPA. An EPA or State of Hawaii-certified laboratory will be used to conduct the analyses for samples submitted.

The final locations established for monitoring will be sampled and measured quarterly. Data from each site will be processed and checked. Quality Control/Quality Assurance procedures will be in compliance with standards of practice for similar programs relative to the acquisition, reduction, verification, and validation of the site data.

In compliance with permit conditions, semi-annual reports of the data will be submitted along with the project status reports on February 15 and August 15 of each calendar year.

PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

H1. INTRODUCTION

This document provides the basis for the Hydrologic Monitoring Program (HMP) for the Puna Geothermal Venture. The HMP is complementary to two additional environmental compliance monitoring programs also being submitted by PGV for their proposed activities at the site. The other two programs are the Meteorology and Air Quality Monitoring Program (MAQMP) and the Noise Monitoring Program (NMP), being submitted concurrently.

The HMP is organized into the following eight chapters, which make up the entire program:

Chapter H1, INTRODUCTION, presents the background, purpose, and scope of the monitoring program. Chapter H2, HYDROLOGIC ENVIRONMENT DESCRIPTION, presents background about the geology, hydrogeology and hydrochemistry of the site vicinity based on previous studies. Chapter H3, PROGRAM DESCRIPTION, describes the activities associated with the proposed program. Chapter H4, SITE DESCRIPTIONS, identifies characteristics associated with the expected monitoring locations. Chapter H5, MONITORING EQUIPMENT AND OPERATION, describes the type of equipment to be used in the measurement, sampling, and analyses of the ground water. Chapter H6, DATA REPORTING, presents the manner in which the monitoring program data will be reported. Chapter H7, QUALITY ASSURANCE PROGRAM, identifies the quality control and quality assurance procedures that will be incorporated as part of the program. Chapter H8, REFERENCES, lists the references cited throughout the text, and in the Figures, Tables, and Appendices. Appendices H1 through H3 contain support documentation for the proposed program.

H1.1 BACKGROUND SUMMARY

On October 3, 1989, the County of Hawaii Planning Commission approved a Geothermal Resource Permit (GRP) GRP 87-2 allowing PGV to proceed with development of a geothermal energy source in the State of Hawaii. PGV will build and operate this 25 MW geothermal energy plant on the Big Island of Hawaii, about 25 miles south of Hilo (Figure H1-1). The project is expected to be producing power in late 1990 from a central production facility situated in an agricultural and rural setting about 3 miles southeast of the town of Pahoa (Figure H1-2). The area is in the Lower East Rift Zone (LERZ) of the Kilauea Volcanic Area, about 20 miles east of the current eruptive center.

The site area is about 500 acres. Approximately 25 of these acres will be disturbed by up to six drill pads, the plant site, and associated piping. Drilling will take place for up to about two years with an anticipated 10 to 14 wells being required to produce adequate steam and hot geothermal liquid to meet the required production capacity. Well depths are expected to be between 4000 and 7000 feet. Steam and liquid coming to the surface will be injected back into the geothermal reservoir using dedicated wells.

There will not be any emissions, other than fugitive, to air or water under normal operational conditions. Well venting and pipe clean out are intermittent but necessary parts of the development of the project. These actions will be scheduled to minimize impacts.

H1.2 OBJECTIVES AND SCOPE

A Hydrologic Monitoring Program is a requirement of the GRP. The text of GRP Condition #10 associated with the HMP is provided in Appendix H1. The general objective of the HMP as stated, is to:

> "...monitor the shallow ground water immediately prior to, and during, all periods of well drilling, testing, production, and injection activity approved under the Geothermal Resource Permit."

This objective will be met by implementing the proposed monitoring program which is described in detail in the following sections.

The required scope of the HMP, as outlined in Condition #10 of the GRP, requires that the following actions be conducted as a minimum:

- Provide quarterly monitoring of water levels and appropriate chemical species:
  - from existing wells completed in the shallow aquifer in those areas downgradient of the project area,
  - from the Green Lake water supply, and
  - from a well located within the project boundary and completed within the shallow aquifer.

- Submit the data obtained from this program on a regular basis as outlined in the GRP.

PGV's proposed scope for the HMP consists of the following seven tasks:

Task 1: Review and update, with selected field measurements, the well data files for existing, non-geothermal wells in the site vicinity,

Task 2: Identify where the two site monitoring locations will be within the project boundary,

Task 3: Rehabilitate the GTW III well east of the project area,

Task 4: Drill and complete two on-site monitoring wells,

Task 5: Document background conditions for the selected wells by conducting the initial round of water level measurements and water sampling at all monitoring wells and water supply locations prior to beginning of injection of geothermal fluids,

Task 6: Continue the proposed monitoring program by conducting measurements and selected sample analyses on a quarterly basis thereafter, and,

Task 7: Provide data reports as required.

Two other Permit conditions are, in part, related to ground water, but, since they relate to potential upset conditions for the project, any necessary response actions go beyond the scope of the routine HMP. They require, in the event of shallow ground water contamination being caused by the project construction or operation (Condition #11) or the Green Lake Water Supply becoming contaminated as a result of the project (Condition #13), that the source of the contamination be eliminated and that an alternative water supply for Green Lake be provided.

PGV will immediately notify the County Planning Department and the DOH in situations when a change in geothermal well conditions indicates there is a leak or failure in the production or injection well casing. PGV will take the appropriate steps to test the production/injection system in question and evaluate the related well and casing downhole conditions. If leakage of geothermal waters to the shallow aquifer is demonstrated, the well would be shut in accordance with GRP Condition #11, and an assessment of the potential impact on the shallow aquifer would be made by the monitoring contractor. In addition, appropriate steps would be identified to evaluate the impact as it relates to downgradient water users.

H2. HYDROLOGIC ENVIRONMENT DESCRIPTION

The purpose of this chapter is to present an overview and summary of what is known about the geologic, hydrogeologic, and hydrochemical setting of the near surface, shallow ground waters at the site and surrounding vicinity. Local conditions, wells, and related features relative to the site hydrologic system are shown on Figure H2-1.

Investigations related to the geothermal development of the area have been ongoing in the site vicinity for about 20 years. Much of the work has evaluated the geologic setting and hydrothermal characteristics associated with the deeper reservoirs below the shallow ground water. Details of the background studies conducted in the 1970s and early 1980s are included in several reports developed by Thermal Power Company (TPC), the previous operators of the PGV project. Three specific studies done which include much of the pertinent data and information related to the hydrogeology and hydrochemistry of the shallow aquifer system at the site include Kroopnick (1978), Weiss Associates (1983), and Thermal Power Company (1986).

H2.1 GEOLOGIC SETTING

The purpose of this section is to present a summary of the geology that has been described by other investigators for the site area.

The project site is in the southeastern part of the Island of Hawaii within the Lower East Rift Zone (LERZ) of Kilauea Volcano. The area is characterized by vesicular, young, sub-aerial basalt lava flows and high annual rainfall.

Weiss (1983, p. 4) reports the following related to the rift zone and the dike systems that influence the areas vulcanism and geology:

> "(The rift zone)...is a zone of linear fissures, faults, cones, dikes and other volcanic features that extend from the Kilauea crater east...(to the ocean).
>
> The basalts that originate along the rift form gently sloping layers of several inches to more than one hundred feet thick. Along the rift, the dikes feeding the flows form vertical walls of dense basalt, and a structure of many closely-spaced vertical dikes results in the near horizontal, less dense flows."

The general geologic setting is, therefore, progressively younger overlying lava flows at depths extending from thousands of feet up to the surface, cut vertically along the rift zone by an east-west trending dike system. In the immediate site area, a north-south trending transverse fault and potentially associated dikes cross-cut the easterly rift zone trend and are thought to be directly linked to the upward migration path for geothermal waters in the area (Figure H2-1).

H2.2 HYDROGEOLOGIC SETTING

The purpose of this section is to present a summary of the understanding of the ground water flow systems active in the site and surrounding area.

The occurrence of ground water in Hawaii was summarized in general by Weiss (1983, p. 13) based on the results of many earlier investigations by the U.S. Geological Survey, Hawaii DOH, University of Hawaii researchers, and other local experts. They identified four main types of ground water in Hawaii, all of which are potentially occurring in the site and surrounding vicinity. They are basal, perched, dike-confined, and geothermal. Figure H2-2 is a cross-section conceptually illustrating how these four types of ground waters occur in 'shallow-aquifer' type zones.

H2.2.1 Recharge Mechanisms

The site is characterized as being in an area of relatively high recharge, with ground water flow occurring in interlayered low to high permeability sub-horizontal lava flows. Ground water flow in the site area has two primary and one potential secondary recharge mechanisms. The primary mechanisms are from precipitation and from local upwelling of geothermal fluids. Downgradient flow from Mauna Loa may also occur, but it is unlikely that this secondary mechanism, if present, is as important to the site area. Perched waters may occur in the area, but their existence has not been documented.

Precipitation

Precipitation is one of the three recharge sources to the area. Average rainfall in the area is reported to be from about 110 to 125 inches per year (Weiss, 1983, p. 5; Kroopnick, 1978, p. 11). An estimated 73 percent of the rainfall percolates downward to the shallow ground water table (Eyre, 1977). Recharge to the shallow ground water system underlying the 500 acre site area would be on the order of about 3400 to 3800 acre-feet per year based on the estimated range of rainfall and the percolation percentage provided by Eyre.

Upwelling Geothermal Fluids

The second primary mechanism for ground water recharge at the site area is from upwelling geothermal fluids. The vertical pathways for the geothermal fluids are believed to be first, in fractures and fault planes adjacent to and associated with the dikes and, second, in areas such as the transverse fault that cuts across the site area between KS-1 and the HGP-A geothermal research well (Figure H2-1). The upwelling is further suggested by the characteristics of the shallow geothermal-influenced ground water (Section H2.3) that has been detected at the site to date.

Downgradient Flow

A secondary mechanism for ground water recharge to the area is believed to be from ground water flowing laterally towards the site area from the north and northwest, down slope from Mauna Loa. The dike systems act as local barriers preventing this underground flow from continuing to move downgradient towards the ocean. Instead, the majority of the ground water is believed to change direction moving to both the east and west along the rift.

H2.2.2 Discharge Mechanisms

Discharge from the shallow aquifer systems occurs from three primary mechanisms, evaporation and evapotranspiration, subsurface migration or lateral underflow, and extractions for drinking water and irrigation use. There are no surface streams in the immediate area.

Evaporation and Evapotranspiration

Evaporation and evapotranspiration represent the principal consumptive use in the area. About 25 to 30 percent of the water falling as precipitation is believe to be consumed in this manner (Eyre, 1977).

Subsurface Migration or Underflow

Flow occurs from the site area and discharges down slope towards the ocean. Spring and sub-sea discharge of warm water along the coast south of the project area has been investigated by researchers working in the area. Local precipitation that reaches the shallow aquifer in the dike-controlled or basal flow areas will also move downgradient away from the site, although the rate and direction of flow are not documented.

Consumptive Use

There are a few shallow aquifer sources that provide ground water for drinking and irrigation purposes in the area in or south of the rift zone. The amount extracted at Green Lake is on the order of 50,000 gallons per day (County of Hawaii, Water Supply Department, 1989, written communication). Volumes for the other wells, if they are being used, are not known.

Discharges from private lands from springs and shallow wells directly along the coast also occur, but the quantities are not known and are not going to affect, nor be affected by, the project activity since they are so near to the ocean and will have local recharge from precipitation to these areas.

H2.2.3 Flow System Description

Based on the work and site data analysis done to date, the following flow dynamics are apparently associated with the site ground water movement:

- The net rainfall (precipitation minus evaporation and evapotranspiration) flows downward into a dike-confined flow system underneath the site, recharging both the shallow ground water systems in the dike-confined areas and into any adjacent shallow basal ground water areas.
- Geothermal waters occur at depth beneath the site and are upwelling in the site area mixing with the precipitation recharge.
- Most ground water moving laterally down slope from Mauna Loa does not reach the site area as it is blocked by the rift zone and dikes. Instead, most is diverted and flows along the rift zone, possibly to both the east and west.

Only a few wells exist in the site and surrounding vicinity which are completed in the shallow ground water aquifer and believed to be potentially downgradient from the project area. Table H2-1 lists the wells currently identified as being completed in this zone. No recent water level measurements are available for many of the wells. Their locations are shown on Figure H2-1.

Table H2-1. Wells in the Shallow-Aquifer[1]

Well Name/Number	Elevation	Depth	Last Reported Use
Allison [A]	132	140	Irrigation
GTW-III	563	690	Abandoned
GTW-IV	259	290	Abandoned
Malama Ki [9-9]	274	316	Abandoned
Kapoho [9-6]	287	337	Abandoned
Kapoho Shaft [9]	38	41	Municipal

Footnotes:
1. Data reported in Weiss, 1983, Table 4, p. 26.

H2.3 HYDROCHEMICAL SETTING

The purpose of this section is to summarize what is understood about the hydrochemistry of the shallow ground water aquifer at and in the immediate potential downgradient directions from the site vicinity.

The LERZ is believed to act as a hydraulic barrier as well as a divide for ground water quality. Chloride concentrations north of the rift are generally low, and concentrations south of the rift have been reported to be greater than 1000 mg/l.

Potable water supplies are obtained from the shallow aquifer at three locations: Pahoa, Green Lake (Kapoho), and Keauohana [9-7]. All are more than 3 miles from the site. Pahoa is north of the rift and has good drinking water quality. Green Lake is in the rift zone and has marginal water quality. The Keauohana [9-7] well is south of the rift zone about 6 miles southwest of the site and has good water quality.

Geothermal waters have been believed to be influencing and mixing with the shallow ground water in the site vicinity for some time. In 1986, TPC compiled much of the background geochemical data for wells in the site area. This was done as part of their request to the DOH to have the Underground Injection Control line moved so as to exclude the site and surrounding area from continuing to be designated as a potential underground supply source of drinking water. Results of their study suggested that there was no potential for a potable water supply to be developed in the site area due to the abundance of geothermal-influenced shallow-aquifer waters occurring over a relatively widespread area near and downgradient from the site.

The University of Hawaii (UH) Agricultural Station at Malama Ki and the Allison wells are located south and east southeast of the site. They have elevated temperatures and levels of chloride in excess of 7000 and 750 mg/l, respectively (Weiss, 1983, p. 26). Both wells may be influenced either directly or as a result of mixing with the upwelling geothermal waters from near the site. The Malama-Ki well is not in use. It is located just south of the transverse fault, about one mile south of the project area. The Allison well, previously used for agriculture as an irrigation water source, is topographically downgradient, about two miles east, southeast from the project area.

The GTW III well just east of the project area was drilled in 1961. The initial sampling of shallow aquifer indicated a temperature of about 200°F and chloride levels over 500 mg/l (Weiss, 1983).

Water samples were taken from the shallow ground water during drilling at KS-1, KS-1A, and KS-2 exploration boreholes on the property. Samples were taken in uncased boreholes at depths of about 700 feet, well above the level of the target geothermal horizons. Table H2-2 summarizes the ranges of constituents for these samples. The samples clearly indicate the geothermal nature of the shallow ground water in the immediate site area.

Results of the sampling done to date indicate that the site vicinity has geothermal-influenced waters in the immediate area. Potable water lies to the north of the rift zone and, based on the existing data, will not be affected by the upwelling of geothermal fluids in the area. The relationship of the waters at Green Lake to the upwelling in the site vicinity is not established, although some investigators have suggested they are not connected or affected by the PGV site area. The area near the Keauohana well is too distant and hydraulically lateral from the site and therefore will not likely be affected by site-related upwelling. Potentially downgradient locations at the Allison and Malama Ki wells have non-potable waters that may be mixed with, or be the direct result of, geothermal waters upwelling locally.

Table H2-2. Shallow-Aquifer Water Quality Data from KS-1, KS-1A, and KS-2 Wells[1]

CONSTITUENT	RANGE OF VALUES[2]		
Temperature		115 °F	
pH	8.5	to	9.5 pH units
Na	600	to	1000
K	26	to	94
Ca	53	to	65
Mg	1	to	30
Cl	1100	to	1600
SO_4	74	to	210
SiO_2	80	to	105
Total Fe	15	to	70
TDS	2200	to	3100

FOOTNOTES:
1 - Source of data from internal files from TPC Project.
2 - Constituents values other than pH reported in mg/l unless otherwise shown.

H3. PROGRAM DESCRIPTION

The purpose of this section is to outline the scope associated with the seven tasks associated with PGV's Hydrologic Monitoring Program.

There are no anticipated project effluent discharges to the shallow basal or dike-confined ground water. These waters are believed to occur at depths between about 500 and 650 feet below the plant site and surrounding area. There may be a few wells in the area that provide irrigation-type water supplies. One area near the Kapoho Crater, referred to as Green Lake, will be part of the monitoring program.

The proposed monitoring program has been revised to reflect follow-up discussions that have occurred with both the County of Hawaii Planning Department and the State Department of Health, Safe Drinking Water Branch. The revisions have been to:

1. Add an additional on-site monitoring location to the program so that two monitoring locations within the project area are in place prior to beginning of injection at the site,
2. Attempt to rehabilitate the GTW III monitoring well location just east of the site, thereby providing a third data point upon which to evaluate ground water flow direction in the site vicinity, and,
3. Increase the number of parameter analyses at selected locations for the initial year of monitoring.

The revised program now consists of seven tasks as follows:

Task 1 - Date Base Update
Task 2 - Locating On-Site Monitoring Wells
Task 3 - GTW III Rehabilitation
Task 4 - Completing On-Site Monitoring Wells
Task 5 - Background Sampling Measurements
Task 6 - Continuing Sampling and Measurements
Task 7 - Reporting

Details regarding each of these tasks follow. Locations, measurement and sampling techniques, and data reporting associated with the monitoring program are described in Chapters 4, 5 and 6, respectively.

H3.1 TASK 1 - DATA BASE UPDATE

This task will involve:

* getting permission to access the sites
* review and update the well data for existing non-geothermal wells in the site vicinity (with assistance from DOH and County staff as available).
* make selected field measurements at selected locations.

H3.2 TASK 2 - LOCATING ON-SITE MONITORING WELLS

This task will:

* evaluate the feasibility of using existing geothermal wells on the site to be completed as a monitoring well in the shallow aquifer,
* Finalize the location of the monitoring wells to be located within the project boundary and,
* Obtain permits from DLNR for drilling these wells.

H3.3 TASK 3 - GTW III REHABILITATION

This task will include:

* Getting permission to access the site,
* Sounding the well for depth,

* Mobilizing a drill rig and cleaning out the well, and,
* Sampling the well.

An alternative location for this third hydrologic monitoring point will be developed in conjunction with the County and DOH if rehabilitation efforts are not successful.

H3.4 TASK 4 - COMPLETING ON-SITE MONITORING WELLS

This task will include completing two on-site monitoring wells. If one of the locations involves use of an existing well, then the scope of this task will include those related actions.

H3.5 TASK 5 - BACKGROUND SAMPLING MEASUREMENTS

This task will include documenting background conditions for all selected wells by conducting an initial round of complete water level measurements and water sampling at all monitoring locations prior to beginning of injection of geothermal fluids.

H3.6 TASK 6 - CONTINUING SAMPLING AND MEASUREMENTS

This task will include implementation of the proposed monitoring program by continuing measurements and sampling on a quarterly basis after start of injection.

H3.7 TASK 7 - REPORTING

This task will involve providing reports on a semi-annual basis as required by the GRP.

H4. SITE DESCRIPTIONS

The purpose of this section is to describe the setting of locations associated with the proposed monitoring program.

The locations for the monitoring of ground water conditions are to be finalized based on the results of the initial task activities. At this time, however, there are five known off-site locations, at a minimum, that would be measured and sample analyses obtained, at least for the first year of monitoring. In addition, two on-site monitoring wells will be sampled prior to start of injection. Other locations may be included as a result of the update of the data base for the area.

H4.1 EXISTING OFF-SITE LOCATIONS

There are five of-site locations that will be part of the initial annual monitoring program. These, shown on Figure H2-1, are at the:

- Municipal supply in Pahoa [9-5A,B; 9-11],
- Municipal supply for Green Lake (Kapoho area),
- 'Allison' [A] well on the Pohoiki Road, and
- Unused Malama Ki [9-9] well on the University of Hawaii Agricultural Station, and
- GTW III Monitoring Well

PAHOA [9-5A,B; 9-11]

The town of Pahoa is served by three wells which tap the basal ground water at depths of up to about 800 feet below the surface. The supply is low-temperature, low-conductivity fresh water in a location about 3 to 4 miles upgradient from the site, north of the rift zone.

One of the wells at Pahoa is a proposed monitoring location since it will serve as a source for documenting levels of constituents in non-geothermal ground waters. Coordination with the Hawaii County Department of Water Supply will be maintained so as to supplement, where required, their ongoing monitoring of this public drinking water supply.

GREEN LAKE [9]

This is a municipal water supply that County Officials report comes from a thin layer of fresh ground water overlying brackish or salty water. The supply was developed by excavation to the water level with a bulldozer, installation of piping and refilling the hole, leaving a piping conduit for the water to flow from the source.

The location is included since quarterly monitoring of the Green Lake water supply is a condition of Condition 10 of the GRP. Coordination with the Hawaii County Department of Water Supply will be maintained so as to supplement, where required, their ongoing monitoring of this public drinking water supply.

ALLISON WELL [A]

The 'Allison' well is a private well that has been used in the past for irrigation. Its current use has not been checked yet. It is located just off the Pohoiki Road about three miles east southeast of the site. Weiss (1983, p.26) reports the well is about 140 feet deep and has a reported temperature of about 110°F, chloride level of about 750 mg/l, and conductivity of about 2000 micromhos/cm.

The location was selected as a proposed monitoring location since it may be hydrogeologically downgradient from the site and in an area that is already influenced by geothermal waters. Permission to access the site has been requested. To date, no approval has been granted. When obtained, coordination with the current owner will be maintained so as to supplement, where required, any ongoing monitoring that the owner may be doing for this well.

MALAMA KI [9-9]

The University of Hawaii maintains an Agricultural Research Station in the Malama Ki Research Forest Area just south of the site. A well, located at a ground elevation of about 274 feet, was drilled to a depth of about 316 feet on this property in the early 1960s (Weiss, 1983, p.26). It was not used, perhaps because of its elevated temperature of about 140°F and its chloride levels over about 6000 mg/l. Sampling was done monthly at this location from January 1980 until June, 1981 as part of background studies of ground water in the area (W. Burkhard, personal communication, December, 1989).

The location was selected as a proposed monitoring location since it appears to be potentially downgradient from the site and in an area that is already influenced by geothermal waters. PGV has contacted the University of Hawaii and obtained permission to sample this well. Coordination with the University of Hawaii Agriculture Department will be maintained so as to supplement any ongoing monitoring that they may be conducting.

GTW III MONITORING WELL

This well is currently abandoned and a blockage exists in the well at a depth of about 270 feet below ground surface. The well was drilled as one of four geothermal test wells along the LERZ in 1960 and 1961. It was originally completed to a depth of about 690 feet, about 130 feet below sea level. As noted in Section H2.3, initial sampling done encountered high temperatures of about 200°F and chloride levels over 500 mg/l (Weiss, 1983).

PGV has obtained permission to access the property and clean out the well. A driller has been contracted and should begin work in mid-April. Cleanout is expected to take about one week. PGV will maintain access and sample and measure the well as part of the ongoing Hydrologic Monitoring Program.

H4.2 ON-SITE LOCATIONS

Two monitoring locations will be situated in the south and north half of the project area. This will complement the GTW III location and allow a ground water flow direction to be calculated in the immediate site vicinity. The location in the south part will be as close to the injection site (Wellpad F) as possible. The location in the north part will be near Wellpad A if an existing well is used, or towards the Kapoho-Pahoa Road if a new monitoring well is drilled.

Once the locations are finalized, applications will be submitted, the required permits obtained, and the wells will be drilled, completed, and sampled. The wells will serve as dedicated monitoring wells for the hydrologic monitoring program.

H4.3 ADDITIONAL LOCATIONS

Any other locations identified beyond those described above in Section H4.1 will be added to the monitoring plan and described, along with the rationale for their being included.

H5. MONITORING EQUIPMENT AND OPERATION

The purpose of this section is to summarize the types of equipment and techniques used to perform the field-related measurements and sampling activities of the monitoring program.

H5.1 WATER LEVEL MEASUREMENTS

Water level measurements will be recorded for those wells identified as an integral part of the monitoring program.

Water level measurements will be obtained utilizing an electronic direct contact detection probe with a calibrated cable/tape for direct measurement at the top of the well casing. Calibrated cable/tape length shall be sufficient to measure water levels in the deepest wells identified. The metering device shall be equipped with an audible signal and light to indicate water level contact. Specifications for equipment similar to what will be used for this type of activity are in Appendix H2.

Water level measurements shall be conducted at each individual well prior to any additional testing or sampling of that particular well. All measurements will be obtained utilizing standard protocols for the equipment described in a separate 'Operating Procedures' document to be finalized as the program is implemented in the field.

H5.2 WATER QUALITY SAMPLING AND ANALYSIS

Water samples will be obtained from each of the wells identified for determination of selected physical and chemical characteristics of the waters from those wells to which access can be readily obtained.

Samples will be obtained from each well according to the characteristics of that well. Wells equipped with pumps will be sampled from the most suitable ported connection. Those wells not in use or not equipped with pumping devices shall be sampled with a stainless steel bailer lowered into the well by winch line to retrieve the volume of water required for each sample.

At each sampling location, standardized equipment cleaning will be carried out prior to obtaining each sample. Protocols to be used for sampling will be provided in the supplemental 'Operating Procedures' document to be finalized when the program is implemented.

Selected parameters values will be determined at each site upon retrieval of the water samples from the well. The field analysis will include measurement of:

- pH,
- temperature,
- conductivity,
- salinity, and
- chloride.

These measurements will be obtained by using calibrated instruments specifically designed to directly measure these physical and chemical parameters within the operational constraints dictated by site conditions. Specifications for equipment similar to what will be used for this type of activity are in Appendix H2.

Water samples will be submitted for the remainder of the analyses to an EPA or a State-certified laboratory. Samples will be transferred from the bailer/sample port directly to appropriately prepared containers supplied by the laboratory. Samples will be labeled, and stored and transported in a chilled state in insulated containers to the laboratory.

Parameters for analysis by the laboratory will, at least for the first year, include selected parameters that are related to underground waters that provide a public drinking water supply. These parameters are listed in Table H5-1.

In addition, the initial year of sampling at all monitoring locations will include, as requested by the DOH, analyses for other organics and other parameters recommended by DOH. These are listed in Appendix H3. After the first year, sampling will not include all of these parameters since there are no sources for many of these constituents associated with the project.

In addition, analysis will be done for the following five constituents which can be associated with geothermal reservoirs:

* Lithium
* Vanadium
* Boron
* Silica
* Bromine
* Nickel

The results of the quarterly sampling will be reviewed at the end of the first year to determine if there is a need to supplement the analysis or if the number of parameters can be reduced. Any recommendations for modification to the sampling program would be included with the semiannual report and submitted to the county for approval.

Table H5-1. List of Water Sample Parameters for Routine Analyses

	Drinking Water Maximum Contaminant Levels
Inorganic Constituents	
Arsenic	0.05
Selenium	0.01
Mercury	0.002
Cadmium	0.010
Lead	0.05
Chromium	0.05
Barium	1.0
Silver	0.05
Secondary Constituents	
Total Dissolved Solids	500.0
Color	15. color unit
Copper	1.00
Foaming Agent	0.50
Iron	0.30
Manganese	0.05
Odor	3.00 ton
Sulfate	250.00
Zinc	5.00
pH	6.50 - 8.5 scale
Corrosivity	Non-corrosive
Other Constituents	
Lithium	
Vanadium	
Boron	
Silica	
Bromine	
Nickel	

H6. DATA REPORTING

The purpose of this section is to summarize the frequency, content, and format for the hydrologic monitoring program data.

H6.1 FREQUENCY AND CONTENT

In compliance with permit conditions, semi-annual reports of the data will be submitted thereafter, along with the project status reports on February 15 and August 15 of each calendar year. The initial submittal will include information regarding all well locations, and as-built diagrams relative to GTW III and the on-site monitoring locations.

Subsequent reports will be in letter format and will include activities conducted during that period, laboratory results of sampling conducted, and recommendations as required.

H6.2 FORMAT

Reporting format will incorporate standard forms and reporting protocols established for similar environmental compliance monitoring programs. The forms and protocols may be modified to reflect the project specific conditions.

H7. QUALITY ASSURANCE PROGRAM

In any program that requires a substantial data base, the credibility of the data must be assured before any derivations from it can be reasonably made. In monitoring programs, the two types of activities necessary to assure the validity of the collected data are Quality Control (QC) and Quality Assurance (QA). Quality Control activities are the primary avenue by which the data are kept within prescribed control conditions. The field QC activities are carried out by the site technician while in-house QC activities are performed by experienced personnel involved with the data reduction and analyses. Quality Assurance activities ensure that each QC activity is performed and documented completely and accurately. A control loop is thereby formed such that if a QA check indicates that an out-of-control condition has been allowed to occur, then the related QC activity will be modified or strengthened to eliminate future occurrences.

All activities of the PGV hydrologic monitoring program will be conducted in compliance with a strong and effective quality assurance program. This program will be managed in accordance with other similar environmental compliance monitoring projects to a standard similar to that expected by the EPA. Details of the QC/QA plan established for this project's hydrologic monitoring program will be submitted as a supplement after details of proposed sampling and measurement activities have been finalized.

Quality assurance also plays a key role in data reduction and analysis and will be performed on a regular basis by a trained professional hydrogeologist. Activities of the Quality Assurance program are designed to ensure overall accountability, traceability, and repeatability.

H7.1 QUALITY CONTROL ACTIVITIES

All equipment will be calibrated prior to use at the site in accordance with manufacturers' specifications. Program technicians will be fully trained in the use of field equipment and performance of field measurement and sampling actions.

Quality Control activities shall incorporate the use of the Standard Operating Procedures (SOPs) for well measurement, sampling, and equipment cleaning developed from U.S. EPA Sampling Protocols. These will be included in the supplemental 'Operating Procedures' document.

Calibration and use of equipment shall be conducted in accordance with Standard Operating Procedures developed for each type of equipment and the manufacturer's recommendation for operation and calibration of each unit.

H7.2 DATA QUALITY ASSURANCE ACTIVITIES

Quality Assurance related to all project measuring and sampling activities will include documenting that field activities were conducted in accordance with the required procedures and recording all field data on forms in accordance with the monitoring contractors standard internal Quality Assurance program.

Quality Assurance related to water sampling shall also include the use of blind duplicates, field blanks, and trip blanks as required to assure environmental control and external laboratory quality assurance.

Data will be reported by the hydrologic consultant, and interpretations and calculations will be checked independently.

H7.3 LABORATORY QUALITY ASSURANCE ACTIVITIES

The laboratory selected for analysis of the samples generated during this monitoring program shall be certified by the EPA or the State of Hawaii Department of Health to conduct those analyses required in this investigation.

Laboratory Quality Assurance is the responsibility of the laboratory. However, the laboratory may be requested to provide documentation of its QA procedures for any of the required analyses at any time.

In addition, blind duplicates and field blanks shall be included in each quarterly sampling for a to determine if the test results are reproducible. If required, duplicate samples may be analyzed by a second independent laboratory for reproducibility of results.

Duplicate samples will be provided to DOH for their independent analysis, upon request.

H8.REFERENCES

Eyre, P.E., 1977. A hydrogeologic study of an area around the Hawaii geothermal project well HGP-A, unpublished.

Kroopnick, P.M., R.W. Buddemeier, and D. Thomas, 1978. Hydrology and Geochemistry of a Hawaii Geothermal System: HGP-A, prepared for National Science Foundation Grant GI-38319, Hawaii Institute of Geophysics, Honolulu, Hawaii, 64 p.

Thermal Power Company, 1986. Petition to Modify the UIC Line in the Lower East Rift Zone, Puna, Hawaii, Internal report submitted to Hawaii State Department of Health.

Weiss Associates, 1983. Hydrology of the Puna Area, Hawaii, Unpublished Report for Thermal Power Company, San Francisco, CA.

FIGURES

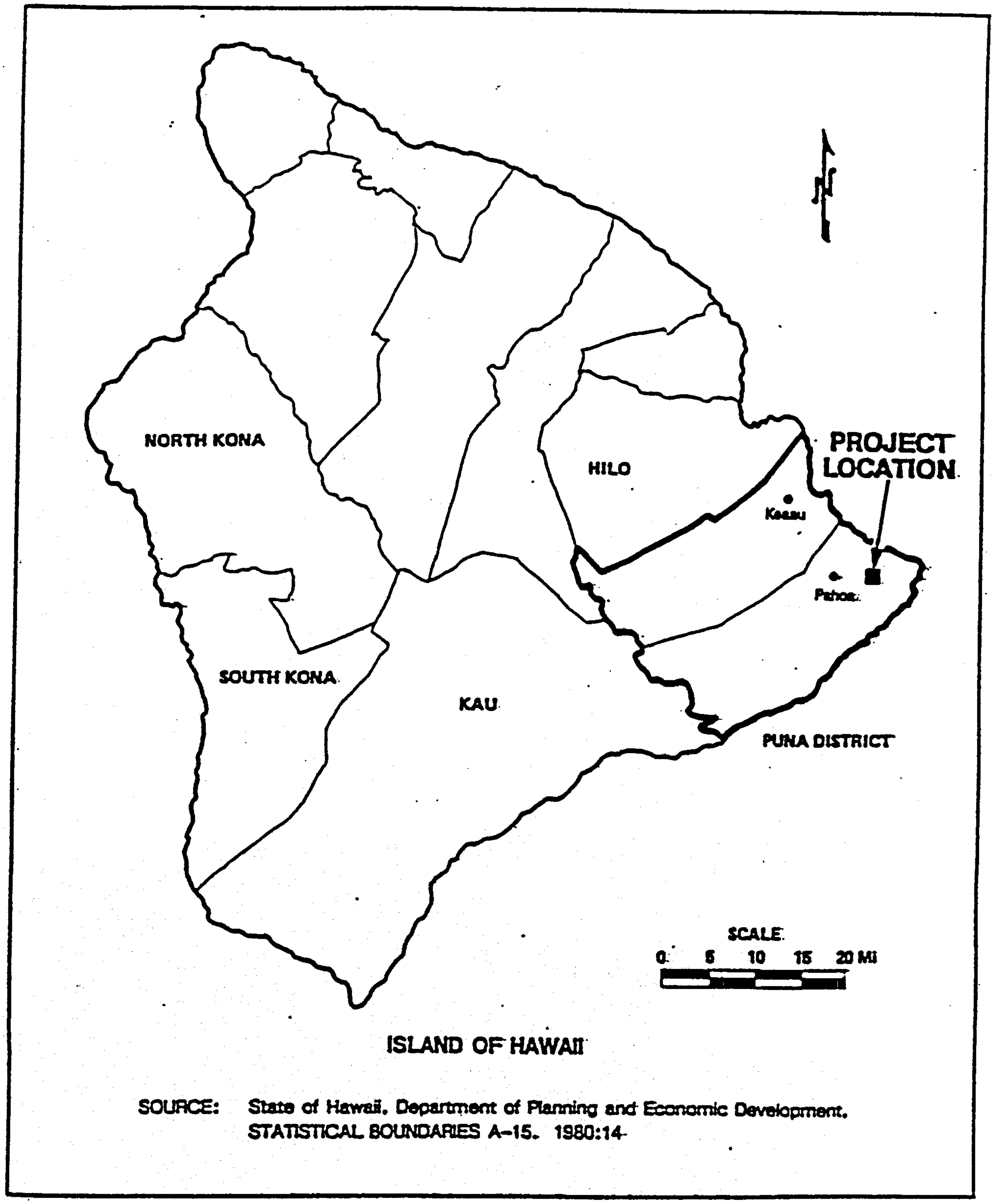


Figure H1-1. Key Location Map

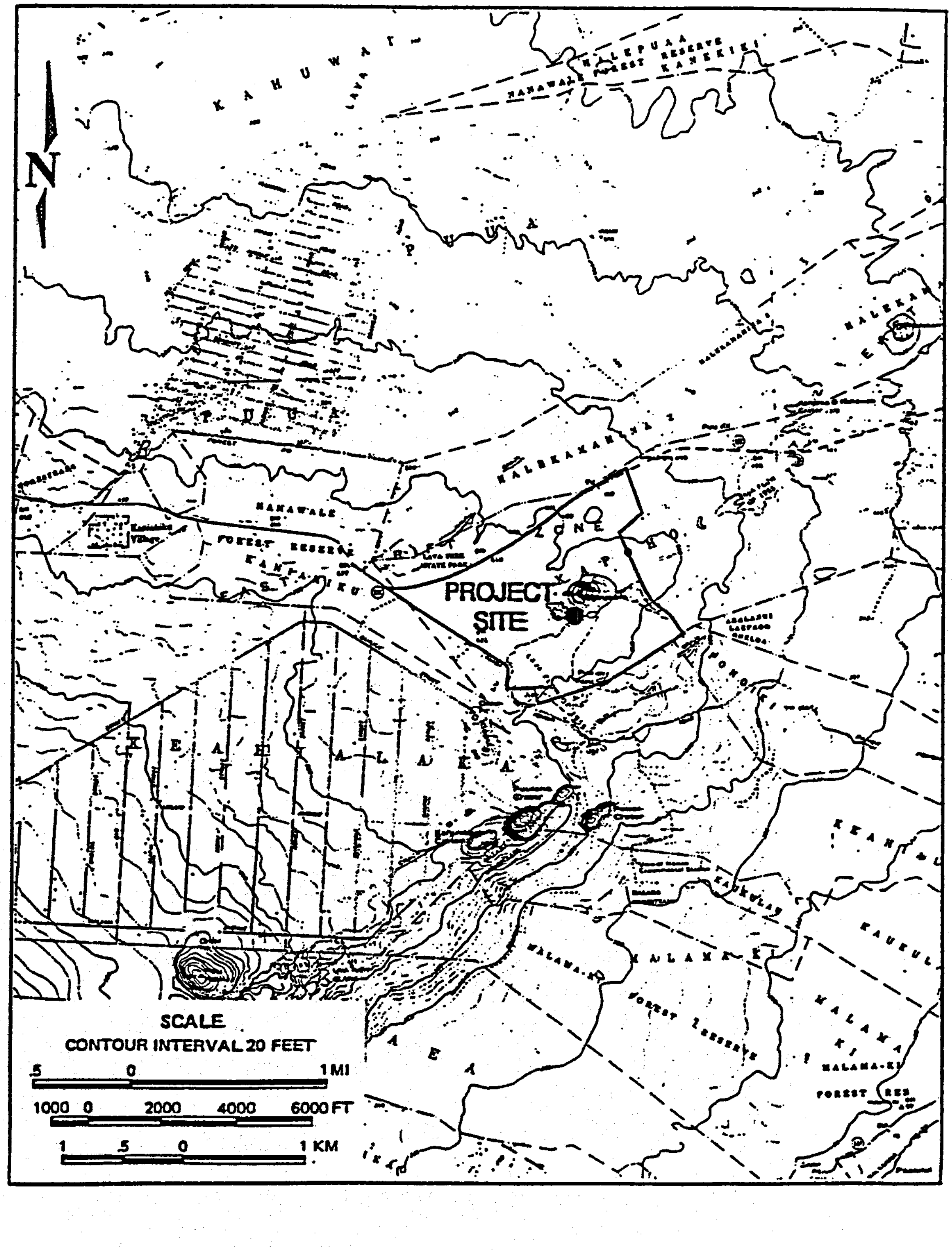


Figure H1-2. Site Vicinity Map

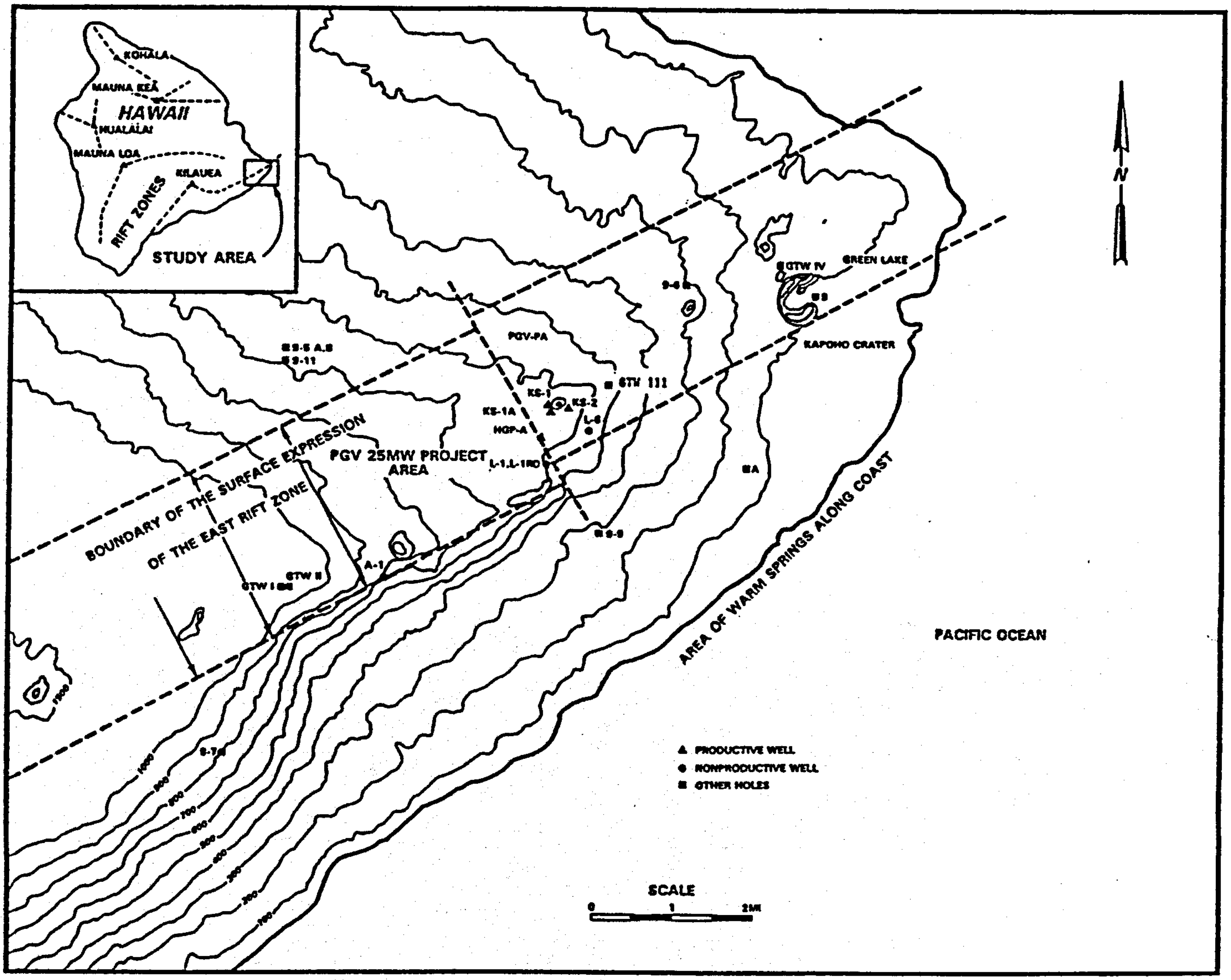
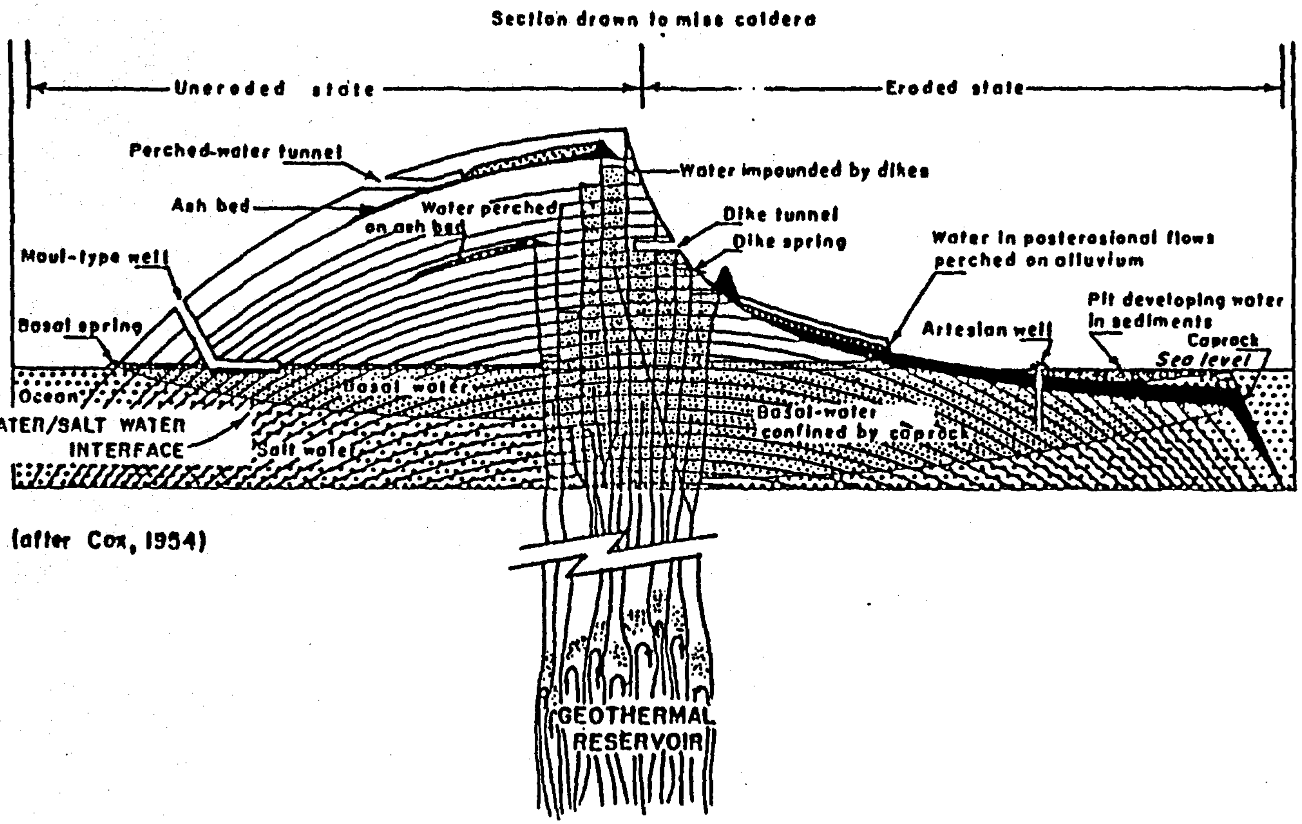


Figure H2-1. Site Hydrologic Data Sources and Related Features



(after Cox, 1954)

Figure H2-2. Types of Ground Water Occurrence and Development in Hawaii

PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

APPENDIX H1

GRP CONDITIONS RELATIVE TO THE
HYDROLOGIC MONITORING PROGRAM

PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM
APPENDIX H1

GRP CONDITIONS RELATIVE TO THE HYDROLOGIC MONITORING PROGRAM

"10. Prior to commencing any geothermal well drilling, testing, production, or injection activity approved under this Geothermal Resource Permit, the permittee shall submit to, and secure the approval of, the Planning Director of a hydrologic monitoring program. The program shall, at a minimum, provide for the quarterly monitoring of water levels and appropriate chemical species from existing wells completed within the shallow aquifer in those areas downgradient of the project area, including the Green Lake water supply, as well as from a well located within the project boundary and completed within the shallow aquifer. The monitoring, sampling, and analysis protocols shall be clearly defined in the program submitted to and approved by the Planning Director. The monitoring and sampling shall be conducted by a qualified contractor, and the samples analyzed by a qualified laboratory, selected by the permittee but subject to the approval of the Planning Director. The selected contractor and laboratory shall operate under contract to, and shall be funded by the permittee. The program shall monitor the shallow groundwater immediately prior to, and during, all periods of well drilling, testing, production, and injection activity approved under this Geothermal Resource Permit. The data obtained shall be submitted to the Planning Director in accordance with the requirements contained in this Geothermal Resource Permit for submittal of all collected environmental monitoring data. The County shall make random checks of the ground water supply no less than every two months."

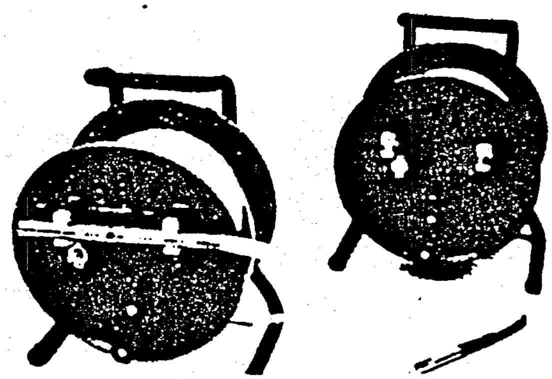
PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

APPENDIX H2

EXAMPLE EQUIPMENT SPECIFICATIONS

Solinst Water Level Meter

MODEL 101



Flat Tape Water Level Meter

For measuring the depth of water in boreholes, standpipes and wells, the Flat Tape Water Level Meter (dipmeter) is the most reliable and accurate of the Solinst Water Level Meters and is easy to operate and read.
Also available is the Model #102 Coaxial Cable Water Level Meter for use in applications with small size tubes.

Operating Principle

The standard Flat Tape Water Level Meter (dipmeter) uses a 0.59" (15mm) diameter probe constructed of nickel plated brass. This is fitted to a permanently marked, medium density, polyethylene flat tape which contains two stranded stainless steel conductors.
The probe itself incorporates an insulating gap around a central stainless steel electrode. When contact is made with water, the circuit is completed, sending a signal back to the cable drum where a clearly audible buzzer is activated.
The water level can then be determined by taking a reading off the cable, at the top of the borehole, pipe or tube. The cable is housed on a high quality storage and winding reel equipped with a brake. The reel has a convenient carrying handle and a sturdy stand-alone design. Standard controls include a battery test button, on/off switch and sensitivity adjustment.

Features

Accurate
markings at cm, 1/2" or 1/20" intervals.
sensitivity control which adjusts to suit water conductivity.

Reliable
permanent, hot stamped markings.

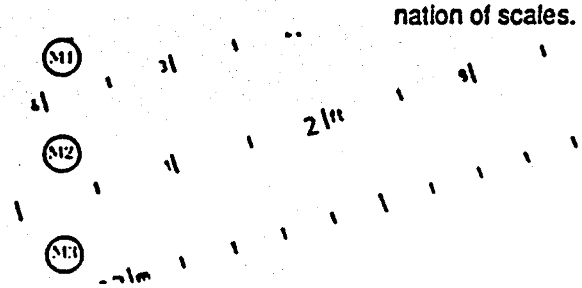
Long Life
rugged, free standing reel.
corrosion proof components.
standard 9v battery.
replacement probes and cables available.

Flexible
lengths up to 1650 ft. (500m).
stainless steel probe and other options available

Measurement Options

The flexible, polyethylene flat tape gives very accurate readings because the permanent markings are at close intervals. The high strength stainless steel conductors provide strength and the design prevents it from adhering to wet surfaces in boreholes and tubes.
Markings are permanently embossed onto one side of the tape and are available in your choice of three scales or, if preferred, any combination of scales, one on each side.

M1 Feet and Inches : with markings every 1/2"
M2 Feet and 10ths of feet : with markings every 1/20ft.
M3 Meters and centimeters : with markings every cm.
M4 Markings both sides : any combination of scales.

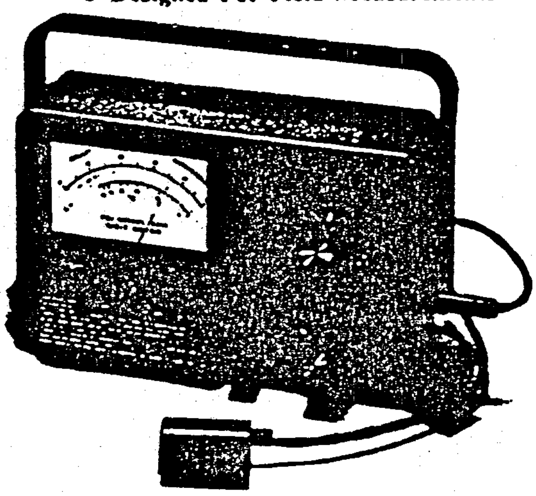


EI

Conductivity Meters

S-C-T Meter
YSI Model 33

- Measures Salinity, Conductivity, Temperature
- Direct Reading Water Quality Meter
- Portable, Battery-Powered
- Designed For Field Measurements



INSTRUMENT SPECIFICATIONS

Conductivity Ranges:
0 to 50,000 μmhos/cm in three ranges. Readability 5% of scale. Error less than ±3% of reading (plus probe).

Salinity Range:
0–40 PPT from −2 to +45°C, readability 0.2 PPT. Error above 4°C less than ±1.1 PPT at 40 PPT, ±0.7 PPT at 20 PPT, plus probe.

Temperature Range:
−2 to +50°C, readability 0.15°C from −2 to +37°C. Error ±0.1°C at −2°C, ±0.6°C at 45°C, plus probe.

100 or 600 Hz Operation:
100 Hz for 500 μmho range, optional 600 Hz for higher conductivity and salinity ranges.

Ambient Temperature:
Operates from +5 to +45°C. Max. drift 0.1% of reading per °C change in ambient. Negligible drift if red line is adjusted.

Probe:
Integral conductivity/temperature probe of durable plastic 1¼" dia. x 2" long (3 x 5 cm), constant of K = 5 ±0.1 cm^{-1}. Error less than ±2% of readings for salinity and conductivity, ±0.1°C for temperature measurement at 0°C, ±0.3°C at 40°C. Probe electrodes can be replatinized by using the instrument plus platinizing solution.

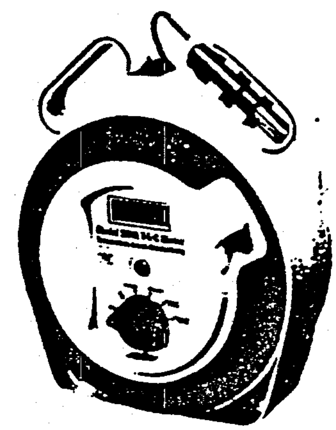
Power Supply:
Two Eveready E95 batteries or equivalent provide 200 hours operation.

Instrument Size:
9 x 16 x 25 cm; 2 kg (3½ x 6½ x 10 in., 4 lbs.)

Ordering Part Numbers:
YSI Model 33 S-C-T Meter
YSI 3310 S-C-T Probe, 10' lead (3m)
YSI 3311 S-C-T Probe, 50' lead (15m). For longer leads to 100', place an "X" after probe number and specify length. Probes 50' or longer supplied with storage reel. For leads over 100', contact factory.
YSI 3140 Platinizing Solution, 2 oz.
YSI 5890 Carrying Case

T-L-C Meter
YSI Model 3000

- Portable, Self-Contained Water Quality Meter
- Measure Temperature, Level, Conductivity
- Groundwater or Surface Water



INSTRUMENT SPECIFICATIONS

Temperature:
Range: −5.0 to +50.0°C. *Accuracy:* ±0.3°C including probe. *Resolution:* 0.1°C.

Level:
Range: 0 to 150 ft. *Accuracy:* ±1" per 50' of cable.

Conductivity:
Nominal Range: 0 to 2.000 millimhos/cm (0 to 2,000 μmhos/cm). 0 to 20.000 millimhos/cm (0 to 20,000 μmhos/cm). *Accuracy:* ±3% of full scale including probe. *Resolution:* 1 part in 2,000.

Temperature-Compensated Conductivity:
Nominal Range: 0 to 2.000 millimhos/cm (0 to 2,000 μmhos/cm). 0 to 20.000 millimhos/cm (0 to 20,000 μmhos/cm). *Accuracy:* ±4% of full scale including probe. *Resolution:* 1 part in 2,000.
Note: Range actually ends at 1.999 or 19.99.

Probe and Cable:
Probe has CPVC body and removable stainless steel weight attached to durable polyurethane-jacketed cable. Probe has 1" nominal diameter, 4¼" length. Cable is 150' long with depth markings every 12"; a water-tight MS connector attaches cable to instrument. Cell constant is K = 5.0/cm ±0.1. Error less than ±2% of readings for conductivity, ±0.1°C for temperature.

Ambient Temperature:
0 to 50°C.

Humidity:
Operates under any humidity condition if seals are intact and desiccant is in place.

Case:
Water-tight to MIL-T-28800C; weighs 7.5 pounds.

Power Supply:
Six "C" size heavy-duty carbon-zinc batteries provide better than 1200 hours operation based on 4 hours use per day. Alkaline cells provide better than 1700 hours. Low-battery indicator warns when to replace batteries.

Ordering Part Numbers:
YSI Model 3000 T-L-C Meter
YSI 3040 Test Probe (tests calibration)
YSI 3050 Replacement Probe, Cable and Reel Assembly
YSI 3140 Platinizing Solution, 2 oz. (for probe maintenance)
YSI 3045 Platinizing Instrument (for probe maintenance)

EI

pH Meters

ORION SA 250 Portable pH/mV/temperature Meter For Hand-held And Bench-top Use.

The SA 250 meter is supplied with a best-performing ROSS. combination, epoxy-body pH electrode and ATC probe for fast, accurate pH, no matter what the sample temperature.

ADVANCED FEATURES

pH Autocal. or manual buffer entry.
Choice of display resolution.
Adjustable isopotential point.
Automatic temperature compensation.
"No slip" grip fits comfortably in one hand.
Durable, dust and splash resistant.
Line or battery operated.

SIMPLE TO USE

Prompting, by advancing to next step.
Assistance (error) codes.

THE SA 250 METER IS FOR THE CUSTOMER WHO WANTS:

An accurate and portable pH system.
A pH meter that is supplied complete and ready to use, with all the accessories you need to make pH measurements in the field or lab.

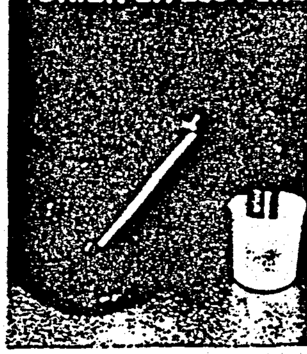
025000 SA 250 Portable pH/mV/temperature Meter for hand-held/bench-top use. Digital, LCD meter comes with carrying case, Model 81-56 ROSS pH electrode, ATC probe, attached shorting plug, one 3M KCl 2 oz. bottle of filling solution, three 60 ml solution bottles, one plastic beaker, electrode holder, support rod, rod guide, one packet pH 7 buffer, one 9V battery, instruction manual, and training guide.

OPTIONAL ACCESSORIES FOR SA 250, SA 230, AND SA 210 METERS.

020041 Shoulder strap and meter holder for hands-free operation. Great for plant or field work

020045 Stable electrode stand with heavy base, rod, and holder.

ORION SA 230 Portable pH/mV/temperature Meter For Hand-held And Bench-top Use.



The SA 230 Meter is shown with a convenient holder that is a sturdy stand for flat surfaces and has a neck strap for hands-free operation.

ADVANCED FEATURES

Automatic temperature compensation.
"No slip" grip fits comfortably in one hand.
Durable; dust and splash resistant.
Recessed control knobs prevent settings from being changed unintentionally.
Line or battery operated.

THE SA 230 METER IS FOR THE CUSTOMER WHO WANTS:

An economical meter with the added accuracy and convenience of temperature compensated pH measurements.

023000 SA 230 Portable pH/mV/temperature Meter for hand-held/bench-top use. Digital, LCD meter comes in carrying case with combination pH electrode, ATC probe, attached shorting plug, three 60 ml solution bottles, one 150 ml beaker, electrode holder, support rod, rod guide, one packet pH 7 buffer, one 9V battery, instruction manual, and training guide.

ORION SA 210 Portable pH/mV Meter For Hand-held And Bench-top Use.

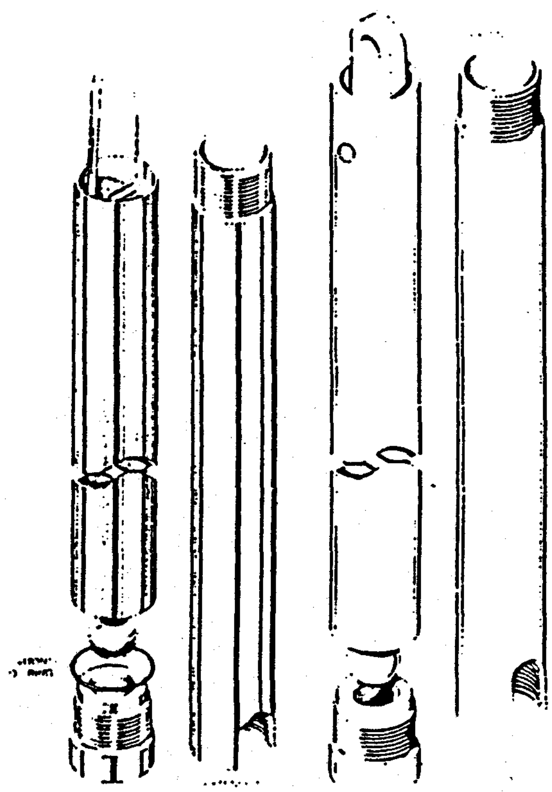
Both the SA 230 and SA 210 Meters have a wide ± 1,999 mV range for economical redox potential determination

Same features as the SA 230, but without automatic temperature compensation or temperature readout, with manual temperature compensation.

021000 SA 210 Portable pH/mV Meter for hand-held/bench-top use. Digital, LCD meter comes in carrying case with combination pH electrode, attached shorting plug, three 60 ml solution bottles, one 150 ml beaker, electrode holder, support rod, rod guide, one packet pH 7 buffer one 9V battery, instruction manual, and training guide

EI

Regular Bailers PVC Teflon® Stainless Steel



Regular Bailers for Well Purging and Sample Retrieval

TIMCO™ bailers are available in Teflon®, stainless steel, PVC and acrylic in sizes from 0.84" to 4.5" (21.4mm—114.3mm) diameter and 1' to 6' (31cm—183cm) lengths.

All are solvent free, and have a flush "V" threaded ball check for ease of decontamination. This design permits the addition of a body extension piece to increase capacity.

The ball check design allows for the inclusion of a Viton® "O" ring in all but the Teflon® opaque model. The Viton® "O" ring provides a leak free joint. It is inert and will not compromise the collected sample.

The bail, an integral part of the bailer body, permits easy attachment of a suspension cord. Stainless steel models have a fixed bail.

(800) 648-9355

PUNA GEOTHERMAL VENTURE
HYDROLOGIC MONITORING PROGRAM

APPENDIX H3

LIST OF ANALYSES FOR FIRST YEAR SAMPLING PROGRAM

Department of Health Laboratories

Form Number ____________

SAFE DRINKING WATER BRANCH
CHAIN OF CUSTODY & EDB/DBCP CONTAMINANT REPORT

Water System Name ____________ Number ______

Sample Location ____________

Well Log # ________-____ Sample Point # ______-___

Type of sample: Routine__ Special ____________

Collection remarks ____________

Sample Chlorinated Y___, N___, ?____

Sampler(s) ____________, ____________

Date: ____________ Time: ____________

Sample Location

Relinquished by: Date/Time	Received by: Date/Time
Dispatched by: Date/Time	Rec'vd for Laboratory by: Date/Time

Method of Shipment: ____________ Seal Intact: Yes__________

Sample Lab # Relinquished by: Date/Time	Received by: Date/Time
Sample Lab # Locked in Refrig Date/Time	Rem'vd from Refrig Date/Time

Regulated Compound	ND	NQ	RESULT*	Method	Date	Analyst	Lab #
Ethylene Dibromide	< .	< .		A B C D			
1,2-Dibromo-3-Chloropropane	< .	< .		A B C D			

1/90

* Measured in micrograms per liter (ug/l) unless otherwise specified.

Methods:
A=Purge Trap
B=GC
C=GCMS
D=Other ____________

Sample Preservation:
HCL (Circle) Y N

Dechlorination:
appx 3 mg $Na_2S_2O_3$

Reported by: ________ Date: ________ QA Check: ________ Date: ________

Forwarded by: ____________ Date: ________

TEST	contaminants	maximum contaminant levels*	lab results*	analytical method	date analyzed	analyst	lab number
	Arsenic	0.05					
	Selenium	0.01					
	Mercury	0.002					
	Cadmium	0.010					
	Lead	0.05					
	Chromium	0.05					
	Barium	1.					
	Silver	0.05					
	Nitrate (as N)	10.					
	Fluoride						
	Chloride	250.					
	Total Dissolved Solids	500.					
	Sodium						

*Measured in milligrams per liter (mg/l) unless otherwise specified.

Analytical Method:

A - Atomic Absorption
B - Atomic Absorption; Chelation-extraction
C - Atomic Absorption; Flameless
D - Atomic Absorption; Flameless Graphite Furnace
E - Atomic Absorption; Gaseous
F - Cadmium Reduction
G - Colorimetric with preliminary distillation
H - Electrode
I - Gas Chromatography
J - Gravimetric Analysis
K - Silver Diethyl-dithiocarbonate
L - Titrimetric Analysis
M - __________
N - __________

No. of Containers: ________			Preservative Added (ml)	Signature	Date	Lab. No.
Container:	No. 1	Metals				
	No. 2	Hg				
	No. 3	NO_3				
	No. 4	TDS/CL/F				

Reported by: __________ Date: ______ QA Check: _____ Date: ______

Forwarded by: ____________________ Date: ______

CONTAMINANT	MCL*	lab results*	analytical method	date analyzed	analyst	lab number
Trihalomethanes	0.10		A B C D			
CHLOROFORM			A B C D			
BROMOFORM			A B C D			
CHLORODIBROMOMETHANE			A B C D			
DICHLOROBROMOMETHANE			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			
			A B C D			

*Measured in miligrams per liter (mg/l) unless otherwise specified.

Methods:
A=Purge Trap
B=GC
C=GCMS
D=Other ____________________

Sample Preservation:
HCL (circle) Y N

Dechlorination:
appx 3mg $Na_2S_2O_3$ added to sample
Y N

Reported by:______________ Date:________ QA Check:_________ Date:________

Forwarded by:____ Date:________

Regulated Compound	MCL*	ND	NQ	RESULT*	Method	Date	Analyst	Lab #
Vinyl Chloride	2	<0.3	<1.0		A B C D			
1,1-Dichloroethylene	7	<0.3	<1.0		A B C D			
1,1,1-Trichloroethane	200	<0.3	<1.0		A B C D			
Carbon Tetrachloride	5	<0.3	<0.5		A B C D			
Benzene	5	<0.3	<1.0		A B C D			
1,2-Dichloroethane	5	<0.3	<1.0		A B C D			
Trichloroethylene	5	<0.3	<0.5		A B C D			
p-Dichlorobenzene	75	<0.3	<1.0		A B C D			

Unregulated Compound	ND	NQ	RESULT*	Method	Date	Analyst	Lab #
1. Chloromethane	<0.3	<1.0		A B C D			
2. Bromomethane	<0.3	<1.0		A B C D			
3. Chloroethane	<0.3	<1.0		A B C D			
4. Methylene Chloride	<0.2	<0.6		A B C D			
5. trans-1,2-Dichloroethene	<0.3	<1.0		A B C D			
6. 1,1-Dichloroethane	<0.3	<1.0		A B C D			
7. 2,2-Dichloropropane	<0.5	<2.0		A B C D			
8. cis-1,2-Dichloroethene	<0.3	<1.0		A B C D			
9. Chloroform	<0.2	<0.6		A B C D			
10. 1,1-Dichloropropene	<0.3	<1.0		A B C D			
11. 1,2-Dichloropropane	<0.3	<1.0		A B C D			
12. Bromodichloromethane	<0.3	<1.0		A B C D			
13. Dibromomethane	<0.5	<1.0		A B C D			
14. trans-1,3-Dichloropropene	<0.3	<1.0		A B C D			
15. Toluene	<0.3	<1.0		A B C D			
16. cis-Dichloropropene	<0.3	<1.0		A B C D			
17. 1,1,2-Trichloroethane	<0.3	<1.0		A B C D			
18. Tetrachloroethene	<0.2	<0.3		A B C D			
19. 1,3-Dichloropropane	<0.3	<1.0		A B C D			
20. Dibromochloromethane	<0.3	<1.0		A B C D			
21. Chlorobenzene	<0.3	<1.0		A B C D			
22. Ethyl benzene	<0.3	<1.0		A B C D			
23. 1,1,1,2-Tetrachloroethane	<0.3	<1.0		A B C D			
24. m-Xylene }coelute	<0.3	<1.0		A B C D			
25. p-Xylene	<0.3	<1.0		A B C D			
26. o-Xylene	<0.3	<1.0		A B C D			
27. Styrene	<0.3	<1.0		A B C D			
28. Bromoform	<0.5	<2.0		A B C D			
29. 1,1,2,2-Tetrachloroethane	<0.3	<1.0		A B C D			
30. 1,2,3-Trichloropropane	<0.3	<1.0		A B C D			
31. Bromobenzene	<0.3	<1.0		A B C D			
32. 2-Chlorotoluene	<0.3	<1.0		A B C D			
33. 4-Chlorotoluene	<0.3	<1.0		A B C D			
34. 1,3-Dichlorobenzene	<0.3	<1.0		A B C D			
35. 1,2-Dichlorobenzene	<0.3	<1.0		A B C D			

Unreg Compounds on List 3	ND	NQ	RESULT*	Method	Date	Analyst	Lab #
36. Bromochloromethane	<0.3	<1.0		A B C D			
37. 1,2,4-Trichlorobenzene	<0.3	<1.0		A B C D			
38. Hexachlorobutadiene	<0.3	<1.0		A B C D			
39. Naphthalene	<0.3	<1.0		A B C D			
40. 1,2,3-Trichlorobenzene	<0.3	<1.0		A B C D			

TEST	contaminants	maximum contaminant levels*	lab results*	analytical method	date analyzed	analyst	lab number
	Endrin	0.0002					
	Lindane	0.004					
	Methoxychlor	0.1					
	Toxaphene	0.005					
	2, 4 - D	0.1					
	2, 4, 5 -TP Silvex	0.01					
	Total Trihalomethanes	.10					

*Measured in milligrams per liter (mg/l) unless otherwise specified.

Analytical Method:

G - Colorimetric with preliminary distillation
H - Electrode
I - Gas Chromatography
J - Gravimetric Analysis
K - Silver Diethyl-dithiocarbonate
L - Titrimetric Analysis
M - Purge and Trap
N - ______________________

Reported by: ______________________ Date: __________ QA Check: ________ Date: ______________

Forwarded by: ____ Date: ______________

Jenny

GEOTHERMAL SYSTEM FAILURES: IMPLICATIONS FOR GROUND-WATER MONITORING

The ground-water quality impact of geothermal energy systems has yet to be determined. This article offers a discussion of these systems and the reasons for their failure as they relate to future monitoring.

by Forest L. Miller Jr. and Douglas E. Zimmerman

A U.S. Environmental Protection Agency grant to assess standard and innovative ground-water monitoring techniques and systems applied to geothermal energy development impacts on associated ground-water systems is currently underway. The research effort is directed toward integrating monitoring techniques, legal constraints, production system fault-tree analysis and comprehensive solute transport and geochemical models. Anticipated results will provide means to assess site-specific ground-water geothermal systems and to identify the optimum monitoring methodology and network design to detect ground-water quality impacts. The models will allow an evaluation of potential worst-case impacts on the ground-water system.

Information on approximately 80 geothermal energy system failures was compiled and reviewed during the course of this study. Failures have ranged from minor leaks in pipes and valves to uncontrollable discharge from wells resulting in the release of large quantities of geothermal fluid. Statistical analysis of the data collected provides a comparison of failure rates for different components of a geothermal development. Both a review of worldwide geothermal well- and plant-failure data and a failure analysis utilizing fault-tree techniques to assess the focal points of ground-water monitoring efforts are presented in this article.

Background

The technology for the conversion of geothermal energy to electricity is in a transitional stage of development. The conversion can be performed in a cost-effective manner and the types of equipment necessary to operate safely and consistently are known, but the operating experience accumulated to date is insufficient to assist in estimating failure rates with reasonable precision. Operating experience in the United States is limited to the Geysers Known Geothermal Resource Area (KGRA) which is located 180km north of San Francisco, California. This KGRA is a vapor-dominated system as opposed to the more common liquid-dominated systems, some of which are being developed elsewhere in the United States. The most active areas of geothermal development in the United States are currently the Imperial Valley of California and sites in northern Nevada. Internationally, power production at a significant scale from liquid-dominated reservoirs is on line at Cerro Prieto, Mexico, Wairakei, New Zealand, and several sites in Japan.

A number of technologies are available for the conversion of geothermal energy to electricity. The selection of the power conversion unit is controlled primarily by the chemical and temperature characteristics of the geothermal reservoir.

Generally there are two basic types of systems. The flash system allows the geothermal fluid to flash to steam, which is then used to drive the turbine. The binary system utilizes a secondary fluid, such as freon or isobutane, which is heated by the geothermal fluid to drive the turbine. Both systems are somewhat similar in that they require production wells, a system of pipes and valves for moving fluid from the wells to the plant, a power conversion unit, and in most cases, injection wells for disposal of spent fluids.

Failure Data

The high temperature, pressure and chemical composition of geothermal fluids are conducive to equipment failure (Table 1). A geothermal reservoir is usually located in an active geologic environment containing faults and fractures which increase the difficulty of drilling and the possibility of adverse environmental impact.

Detailed data on geothermal system failures are generally not available. The best-documented failures have been those associated with wells. Unfortunately, even these data are often lacking in such important items as discharge rates, detection method and cause of failure. Failure data on equipment such as surface piping and energy conversion components are also limited (Sung et al, 1980; Summers et al, 1980).

On the basis of failure data collected, a review of geothermal site plans, and consideration of possible fluid release points, the following components were considered for failure analysis:

- wells
- wellhead assembly
- surface equipment
- disposal system.

Production Wells

Well failure can occur in two distinctly different operational modes. Failure can occur during the drilling of the well or during geothermal fluid production. To control the movement of formation fluids around the

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ATTACHMENT 6-A

outside of the well during both drill-ing and production. the well-bore size is reduced with depth. At each reduction in hole diameter, the bore is cased and cemented. An example of the casing and cementing of wells at Wairakei, New Zealand, is shown in Figure 1. Numerous tools and techniques exist for physically locating and defining the type and severity of casing failures, but only a modest amount of data concerning the actual cause of the failure can be acquired when the failure occurs hundreds of meters or more below ground level.

Failures during drilling operations can result in uncontrolled discharge from the well bore. This condition, known as a blowout, is of particular concern as uncontrolled discharge can last a significant length of time. The costs and difficulty of repairs are high. Blowout of a well is possible when the formation fluid pressure exceeds the pressure of the drilling fluid in the well bore. This condition can occur in zones of lost circulation, where the formation being drilled is either very permeable, has an extensive fracture or fault system or is cavernous. Blowout preventers which seal against the drill pipe in the event of a significant pressure drop are required safety equipment during the drilling of geothermal wells.

Many individuals from both private and governmental sectors believe that drilling equipment and technology currently in use have proven sufficient to prevent well blowouts. The incentive to prevent this type of failure is borne by the geothermal developer because of the high costs of drilling operations and subsequent costs of controlling a well blowout. A typical well at the Geysers KGRA costs between $825,000 and $1.6 million to drill and complete.

Because of difficulties in identifying production well failure, the potential for adversely impacting associated ground-water systems is relatively high. Failure of a well casing can range from a minor fracture to a complete collapse. Discharge can be very limited or can constitute the total flow of the well, resulting in a blowout condition. Indications of casing failure can be as obvious as visual discharge at the surface or as subtle as a change in the chemical constituents of the fluid. Other indicators of casing failure include a reduction in flow or temperature, change in the steam/water ratio, or inclusion of sand or other formation

Table 1. Geothermal Equipment Failure Causes

Initial Condition	Resulting Failure Mechanism	Possible Failure Point
High temperature	1. Thermally induced stress 2. Thermal cycling	All components Well casing problems most severe
Poor quality fluids	1. Corrosion 2. Scale 3. Abrasion 4. Dissolved gases	All components
Geologic environment	1. Drilling and cementing problems associated with lost circulation zones	Well casing
High pressure	1. Pressure induced stress	All components
Present stage of development	1. Inadequate materials 2. Inadequate design and workmanship 3. Lack of operating experience	All components
Natural disasters or accidents	1. Landslides 2. Earthquakes 3. Accidents as a result of personnel error 4. Vandalism or terrorism	All components

material in the production fluid. Failure of the cement between the casing and the formation is usually associated with casing failures. This can allow the geothermal fluid to migrate along the well bore and enter a formation different from that in which the original failure occurred.

A number of interrelated factors may contribute to casing failure:

- thermal stresses or thermal cycling
- inadequate cementing of the casing
- corrosion.

The following scenario describes the interrelationships of these factors:

During the drilling of a well, formations are encountered that are highly permeable. When the well is cased and cemented, a poor cement bond between the casing and the formation is achieved in these zones, allowing the casing to differentially expand and contract. The well is completed and put into production. The casing is subjected to high temperature variations causing thermal stresses. (The term thermal cycling is used to describe the expansion and contraction of the casing as it is alternately put on production and then shut in as energy requirements or maintenance of the well or power plant dictate.) The casing subsequently fails in the zone where the cement bond is poor due to the thermal stresses associated with production. Failure can occur very early in the life of a well or can occur much later when the casing is further weakened by both corrosion and thermal cycling.

Analysis of casing failures in the geothermal fields of Italy revealed that failures were more likely to occur after large temperature variations and that the lower part of the casing string was more likely to fail (Cigni et al. 1975).

Again, the difficulty in identifying the exact causes of casing failure should be recognized. Due to the limited amount of data that can be collected, it is difficult to precisely determine the cause of failure. During the time of data collection for this report both the literature collected and discussions with government and private operators have stressed the rapid technological improvements in both drilling and cementing techniques by the geothermal industry. Data from the California Division of Oil and Gas indicate there have been no serious problems with geothermal well drilling in that state since 1975. Indications are strong that improved technology has decreased failure rates in newly constructed wells. As more data is compiled, it may be possible to verify this hypothesis and to identify wells that are more likely to fail by their age.

Wellhead Assembly

The basis for separation of the wellhead assembly from other components of the piping system is the potential for uncontrolled discharge in the event of failure. The wellhead assembly typically consists of several valves which are used to regulate flow from the well. In the event of failure of other surface equipment, these valves could be closed to stop flow from the well. Failure of these valves to close due to either corrosion or scale would then result in uncontrolled discharge. Uncontrolled discharge related to wellhead failure also occurs if the entire wellhead becomes separated from the well casing. This happened at Cerro Prieto, Mexico, but could have been avoided by proper installation of the wellhead assembly.

Surface Equipment

In contrast to the difficulty in identifying and repairing a well failure, failure of surface equipment is relatively easy to detect and repair. Costs of repair are relatively low and, generally, technically straightforward.

All components of the piping system are susceptible to failure as a result of corrosion, abrasion or scale formation. Dissolved gases, particularly H_2S, also contribute to failure. Thermal stress and thermal cycling of above-ground pipes is not as significant a problem. U-shaped sections of pipe are routinely installed in the line to allow for thermal expansion. Corrosion and abrasion can be expected to be higher where the flow impinges directly on the pipe surface, as at an elbow where a directional change in flow occurs.

Data on failure of surface equipment have come mainly from the Geysers KGRA. The principal failure points of the surface equipment have not been associated with the major components found in the power plants but with the pipes and valves which transmit fluid between these components. Generally the failures have been detected and repaired within 60 minutes. Unfortunately, data from the Geysers is very atypical. This is a dry steam reservoir which does not require flashing and the injected condensate has total dissolved solids values that range from 300 to 1,000 mg/l. In contrast to this are sites in the Imperial Valley where brines are produced with total dissolved solids as high as 300,000 mg/l.

Numerous studies have been conducted on corrosion, abrasion and scale formation rates at specific geothermal sites, but extrapolation of these data into failure rates is limited because of the experimental nature, limited time period and wide variation in fluid chemistries during these studies. Corrosion studies of various metal alloys in the Imperial Valley have shown that steels containing either molybdenum or chromium and molybdenum withstand corrosion better than the carbon steel pipes most commonly used (McCright et al. 1980). Because of the lack of operating experience in the United States, estimates of failure rates for surface equipment are based on data from nuclear power plants.

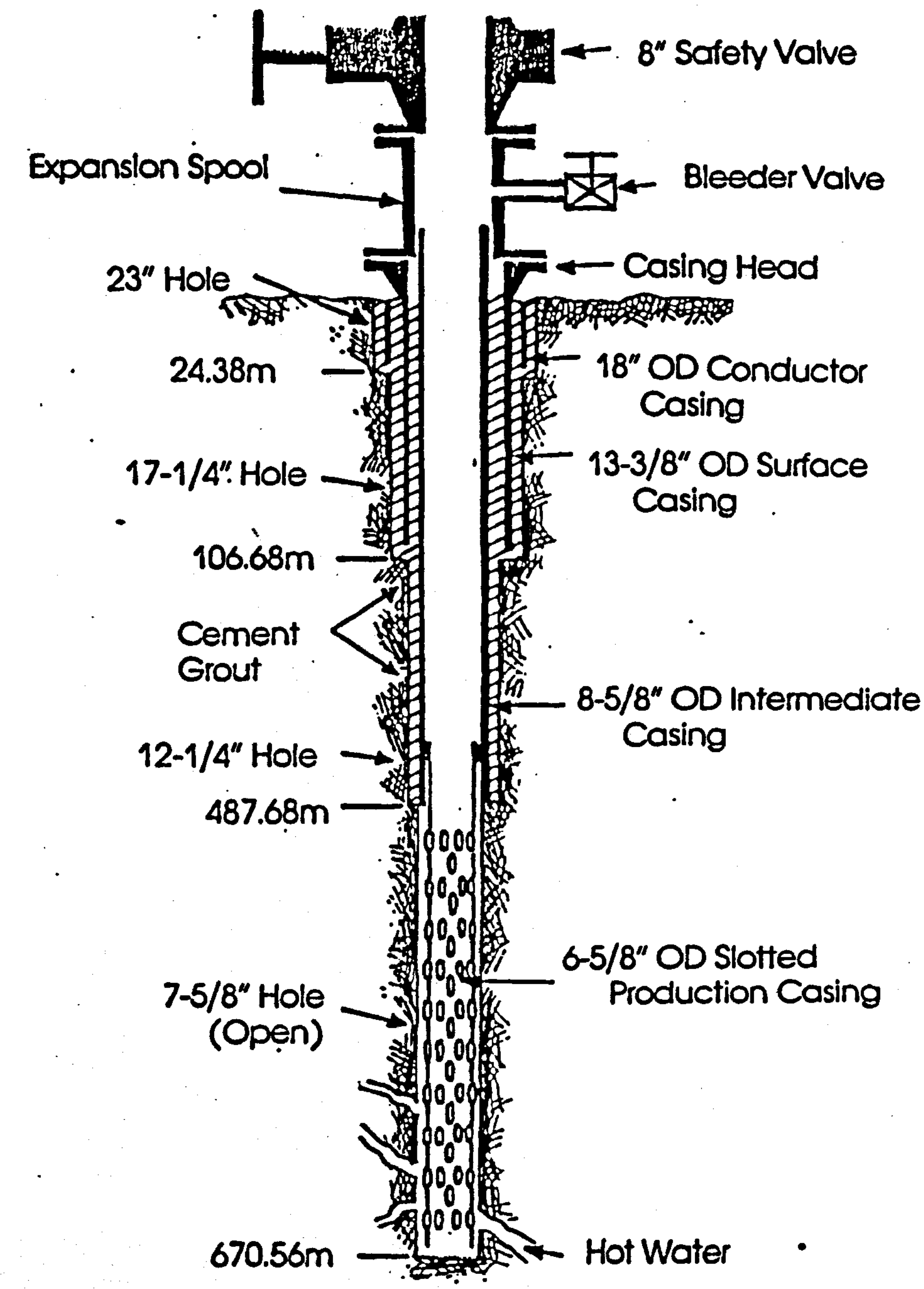

Figure 1. Typical casing design at Wairakei, New Zealand. (after Delferding, 1980).

Failure ...

Data on more than 80 failures (Table 5) were compiled during the course of this investigation (Miller and Zimmerman, 1980). Although most failure reports provided little or no detail on the amount of fluid released, they were valuable in establishing potential release points. Many of the failures occurred because of inadequate well construction materials or lack of operating experience. The most difficult failures to control and the largest releases of geothermal fluid have resulted from production well failures.

For instance, well number Thermal-4, drilled at the Geysers in 1957, blew out during drilling due to inadequate casing and cementing techniques. Attempts at controlling the well have failed and the well is presently discharging to the surface. In 1976, the uncontrolled discharge was estimated at 80,000 kg/hr of steam. A casing break occurred in well number 26 at Wairakei, New Zealand, in April 1960. The well was drilled in 1954 and had produced fluid normally up to the time of the casing failure. The failure occurred at a depth of 183m. Due to flaws and probable deterioration of the cementing around the casing, flow was able to move upward and laterally. Flow discharged at the surface approximately 240m from the well. In November 1960, well 26A was deviation drilled into well 26 below the casing break, stopping the discharge. Total uncontrolled discharge was estimated at 6.17×10^5 tons.

Fault-Tree Methodology

The purpose of applying fault-tree methodology to geothermal energy development is to identify both the possible failure modes which would result in release of geothermal fluid and the possible sites of failure (Barlow et al, 1975). It is convenient to treat as a unit parts of the mechanisms that are structurally identical or parts in which failures would lead to a common effect. For example, the above-surface piping used to move geothermal fluid could be considered on a meter-by-meter basis since a failure could occur at any point. However, the piping from production wells to the conversion plant is designed to common specifications and measures taken at any point to confine a leak would probably be taken throughout the piping system, so the production piping can be considered as a unit. The production piping and injection piping would be considered separately since there are likely to be more corrosion problems in the production piping than in the injection piping while the reverse is true with respect to scaling. The energy conversion system would be considered as a unit since a failure in this system could result in release of fluid to the floor of the building and remedial action would be the same. A fault-tree figure (Figure 2) can be used to provide an overview of the system.

For demonstration purposes, the fault-tree methodology will be applied to a modified conceptual design of a double flash geothermal development presented by Sung et al, 1980. The modified design consists of 28 vertically drilled production wells with 12,200m of associated production piping which will deliver the geothermal fluid to the power plant located 300m from the edge of the well field. The system utilizes 15 vertically drilled injection wells which requires 8,800m of injection piping.

For the purposes of this example, the energy conversion system will be placed on the Roosevelt Hot Springs KGRA, near Milford, Utah. This is a liquid-dominated system with a depth to the top of the reservoir of 820m. We assume that wells drilled in this development will average 900m in depth. The principal ground-water reservoir in the Milford area is the unconsolidated valley-fill alluvium. Well logs reveal that this material is between 60 and 150m thick in the KGRA and it is assumed that each well passes through a vertically unconfined aquifer, A_1, 110m in thickness. Logging of well DH 14-2 revealed a cold water entry zone, between 200 and 230m, which will be treated as if it were a confined aquifer, A_2, of potential importance as a source of domestic or agricultural water.

For convenience we assume that distribution of location of well casing failure is independent of depth. We further assume that an aquifer is only contaminated if the failure occurs within the aquifer. Therefore, if there is a casing failure in the zone of aquifer A_2 the probability (p) of contaminating aquifer A_2 is 1. If the failure occurs elsewhere, the probability of contaminating aquifer A_2 is zero. The probability of contaminating aquifer A_2, given that the well has failed, is the ratio of the thickness of the aquifer to the depth of the well, 30/900, or .03. Likewise,

Reported Flow Rates of Injection Wells in the United States

KGRA	Production Well tons/hr	Salinity	Injection Well l/s
Salton Sea, CA	227	250,000-330,000	—
Westmorland, CA	263	20,000- 70,000	—
Brawley, CA	32	100,000	—
Heber, CA	200	14,000	185**
East Mesa, CA	336	2,500	14
Beowawe, NV	680	1,400	—
Roosevelt Hot Springs, UT	454	7,800	—
Valles Caldera, NM	23	6,000	—
Raft River, ID	—	—	79
Geysers, CA	68*	—	76
Niland, CA	—	—	38

* Average flow rate
**Estimated value

Table 5. Summary of Reported Failures From Geothermal Sites in the U.S., Mexico and New Zealand

Failure Point	Number of Failures
Drilling failure	3
Production well	28
Production wellhead	3
Surface piping	49
Injection wellhead	1
Injection well	None reported

the probability of contaminating aquifer A_1, given a failure in the well, is 110/900, or .12. The probability of not contaminating aquifer A_2 by one or more of the 28 production wells in a given calendar year is p^{28}, where 1-p is the product of the probability that A_2 will be contaminated given a failure (.03) and the probability that a 900m well will fail in a year. Data from the Wairakei field indicates that the probability of a 900m production well failing in a calendar year is about .014. Therefore, the probability that a given well will fail in a calendar year and that it will contaminate aquifer A_2 is .00042. The probability of one or more production well failures in a calendar year which contaminates aquifer A_2 is $1-.99958^{28}$ or .01. This analysis is tentative and further work is required to refine the estimated probability of failure of a well. By identical logic, the probability of failure in a calendar year of at least one injection well which impacts aquifer A_2 is .006.

Using the above reasoning, the probability of contaminating aquifer A_1 during a calendar year by production well failure is estimated to be .05 and the probability of contaminating A_1 by failure of an injection well is estimated to be .02. Injection of geothermal fluid is not done at Wairakei and probabilities computed assume the same life expectancy of injection wells as for production wells.

Probabilities of failure of above-ground components were estimated by Sung et al. 1980, from data compiled in the Reactor Safety Study of 1975 (also known as WASH-1400 or the Rasmussen Report). They estimated that the probability of a major wellhead rupture in this geothermal energy conversion design during the 40-year design life is .008. Further, they indicate, "Minor leaks are to be expected. Each gasket in the system would be expected to fail at least once during the assumed 40-year design life." If we assume that the probability of a major wellhead failure is constant over time, then the probability of a particular wellhead failing in a given calendar year is estimated to be .000005, the probability of there being at least one production wellhead failure in a calendar year is estimated to be .0001, and the probability of at least one injection wellhead failure in a calendar year is estimated to be .00007.

If the probability of failure of piping is 1×10^{-10}/hr/300m (Sung et al.

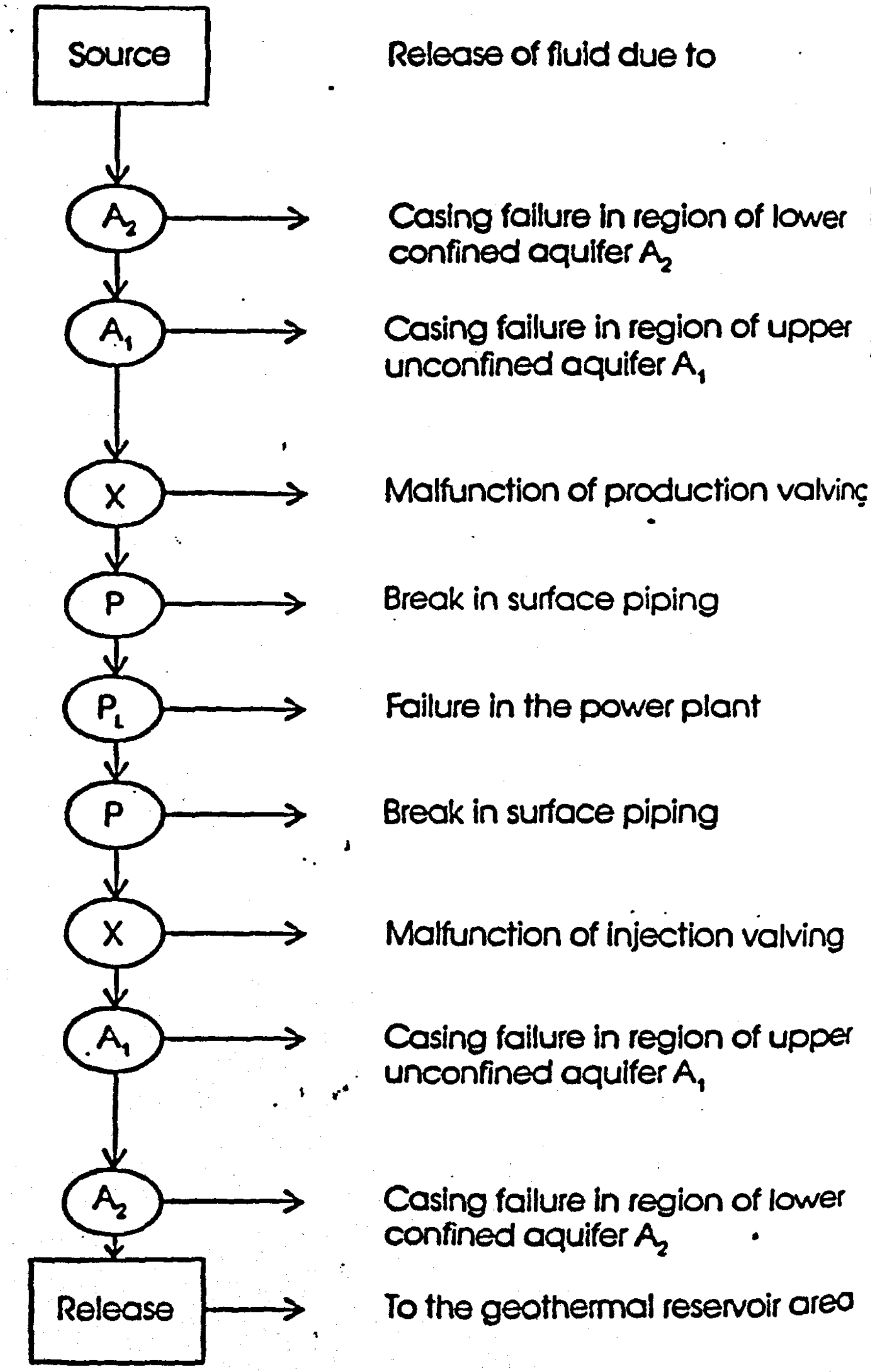

Figure 2. Prototype fault-tree for a geothermal energy conversion system.

1980) then the probability of at least one failure in 12,200m of production piping in a calendar year is .00004 while the probability of at least one failure in 8,800m of injection piping during a calendar year is .00003. These numbers are applicable to piping in a nuclear reactor, built to more stringent specifications than geothermal piping, and the estimated probabilities of failure may be too low. On the other hand, the stresses may not be as severe.

The probability of a major failure of the conversion system during its 40-year design life is estimated by Sung, et al. to be .001. Making the assumption that these failures are distributed uniformly over the 40-year lifetime, the probability of failure in a calendar year is estimated to be .00003.

Fault-Tree Summary

While it is important to acquire more failure data, including data on failures of the same types of equipment in similar environments, it is unlikely that this will lead to satisfactory precision of estimates of failure rates soon because conversion of heat from geothermal fluids to electricity is a relatively recent activity. Because of that, determination of reasonable coefficients of variation for the small probabilities of failure estimated in Table 6 are unlikely until considerable operating experience has been acquired. Table 6 does demonstrate in a relative sense that the highest probability of failure is associated with wells. Since well failures are difficult to detect, can involve large volumes of fluid and can directly impact ground-water resources, the focal points for ground-water monitoring should involve both production and injection wells.

Acknowledgments

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Table 6. Relative Annual Probabilities of Failure of Major Components of a Double Flash Geothermal Conversion System

p	Cause
.01	Production well failure contaminating aquifer A_2
.05	Production well failure contaminating aquifer A_1
.0001	Production wellhead failure (major)
.00004	Production piping failure (major)
.00003	Failure in conversion system (major)
.00003	Injection piping failure (major)
.00007	Injection wellhead failure (major)
.02	Injection well failure contaminating aquifer A_1
.006	Injection well failure contaminating aquifer A_2

Sung, R., W. Murphy, J. Reitzel, L. Leventhal, W. Goodwin and L. Friedman. 1980. Surface containment for geothermal brines. U.S. EPA publication no. EPA-600/7-80-024.

Biographical Sketch

Forest Miller is a research professor at the Desert Research Institute, University of Nevada. He received a BS and MS from Purdue University and a Ph.D. from North Carolina State University, all in statistics. By profession he is a consulting statistician, with research interests in spatial analysis, reliability of complex systems and model evaluation.

Douglas Zimmerman is a research associate at the Desert Research Institute, University of Nevada. He received his BS in geology from San Diego State University in 1975. His primary professional emphasis has been in the design, construction and testing of monitoring and production wells.

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Geothermal power interests 31 firms

By Jim Borg
Advertiser Staff Writer

Declaring that Hawaii's renewable energy needs to override political differences, Gov. John Waihee yesterday announced with Hawaiian Electric Co. that 31 companies have expressed interest in tapping the Big Island's volcano district to provide power for Honolulu.

Waihee and HECO President Harwood D. "Dan" Williamson said requests have been sent to the companies for proposals to build a geothermal power plant and deep-sea transmission cable to Oahu by 1995. It hasn't been decided if Maui would be included en route, said Williamson.

Selection of a private consortium to handle the project is expected by the end of 1990, Williamson said.

Regarding opposition to geothermal power, Waihee said, "I do realize that there are people who are concerned about the development of geothermal energy and there are some that would be against any development, and we just happen to disagree."

Williamson said that among 118 companies queried, 31 expressed interest in the project, which is expected to provide 500 megawatts to Oahu at a capital cost of $1.5 billion to $1.7 billion. No rate hikes are anticipated to pay for the construction, he said.

Current Oahu power use is about 1,060 megawatts, with an increase to 1,300 megawatts expected by the mid-1990s, said Williamson.

"Based on today's electrical demand and current oil prices, satisfactory completion of this project would satisfy a major portion of Oahu's electrical needs, while decreasing oil imports to Oahu by 7.3 million barrels a year at a cost of $160 million," Williamson said. Honolulu is now 97-percent dependent on oil to generate electricity.

"Oil prices are once again moving up in a volatile oil market," said Waihee. "Our economy and standard of living continue to hinge on an energy source which is entirely out of our control. It is time to reverse this vulnerability ... Development of geothermal energy is the key to achieving our state goal of energy self-sufficiency and it is imperative to Hawaii's future that we move forward now."

State-supported test drilling will be conducted over the next few months to determine the potential of the fields, which has been estimated at between 500 and 2,000 megawatts, Williamson said. The transformer station on Oahu will probably be somewhere near Waimanalo, he said.

The interested companies have until Aug. 1 to file a notice of intent to submit a proposal, until Nov. 1 to file technical proposals and until Dec. 1 to file commercial proposals, followed by a year of evaluation and negotiations, Williamson said.

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GEOTECHNICAL REPORT

Geohydrochemical setting of the lower East Rift Zone with special emphasis on the relationship between geothermal fluid injection and Hawaii Department of Health, Underground Injection Control regulations.

Joe Iovenitti

Joe Iovenitti
Senior Geologist
3 July 1986

SUMMARY

Three basic water types: geothermal, fresh and mixed, have been identified in the shallow and intermediate subsurface of the lower East Rift Zone, Puna, Hawaii, Hawaii. Geothermal waters are found proximal to a major structural intersection of the East Rift Zone with a transverse fault. This structural intersection is interpreted to provide the conduit for upward migration of geothermal fluids from the reservoir located in the deep subsurface. The intended PGV 25 MW project lies in this region of upwelling geothermal fluids. Fresh waters are present north of the rift zone and south of the rift in the area southwest of the 25 MW project. Mixed waters are located within the rift near Kapoho Crater which lies down gradient from the region of upwelling geothermal fluids.

The characterization of these water types has been conducted through an integrated geohydrochemical review of the lower East Rift Zone. Utilized in this study were all available geotechnical data, statistical and pattern recognition techniques and set theory.

Thermal Power Company believes that those areas shown to contain geothermal or mixed waters should not be classified as an underground source of drinking water. Current Hawaii State Department of Health Underground Injection Control (UIC) regulations designate a large portion of the lower East Rift Zone region as an underground source of drinking water. Accordingly, Thermal petitions the Department to modify their current UIC line on the Big Island of Hawaii to include those areas demonstrated in this report to contain geothermal and/or mixed waters.

INTRODUCTION

Thermal Power Company, operator of the Puna Geothermal Venture (PGV) which includes Amfac Energy, Inc. and Dillingham Geothermal, Inc., has submitted their description of the PGV 25 MW Project in Puna to State and County agencies. This project is located on the Big Island of Hawaii in the lower East Rift Zone (LERZ) of Kilauea Volcano (Figure 1). Injection of geothermal fluids is an integral part of any geothermal electric power generation project. Concomitant with this requirement is the responsibility of the geothermal developer to protect the quality of underground sources of drinking water (USDW) from pollution by subsurface disposal of fluids.

Protection of USDW in Hawaii is regulated by The Safe Drinking Water Act administered by the Environmental Protection Agency. The State of Hawaii has adopted Chapter 23 of Title 11, Administrative Rules, "Underground Injection Control" (UIC) of Hawaii State Department of Health (HDOH) to receive delegation of Federal authority to administer the UIC program at the State level. A large portion of the lower East Rift Zone is currently defined as an underground source of drinking water by HDOH, UIC regulations. This report reviews the overall geologic, hydrologic and chemical setting of the LERZ. It focuses on the hydrochemical characterization of the shallow (surface to 1500') and intermediate (1500' to 4000') subsurface. Injection of geothermal fluids into the geothermal reservoir from which they originated or into a region surrounding the reservoir at comparable depths is a worldwide practice. Character' .cion of the deep (greater than 4000') subsurface is not warranted herein .ause the geothermal system occupies this position. Whatever upward movement of injected fluid takes place would be negligible relative to what is naturally occurring. Criteria[1] are developed which allows characterization of waters in the LERZ as either a fresh, geothermal, or mixed type. The latter category refers to waters not clearly of the former two types. The current HDOH, UIC regulations are then evaluated with respect to the geohydrochemical setting. Finally, a recommendation is presented to render the Hawaii State UIC regulations consistent with the new technical findings reported herein.

LERZ GEOHYDROCHEMICAL SETTING

Geohydrology

The East Rift Zone is one of the main conduits for the lateral migration of basaltic magma from the holding chamber beneath Kilauea's summit caldera. It is manifested at the surface as a linear and parallel belt, 1-2 miles wide. The rift zone consists of open fissures, faults, small grabens, pit craters, cones and vents related to numerous volcano-tectonic events. In the LERZ, eruptions have occurred as recently as 1740, 1840, 1955, 1960 and 1961. The East Rift Zone is a constructional ridge standing some 500-1500 feet above the adjoining terrain throughout its length except in its lower portion (LERZ) where the ridge disappears into a series of grabens and splatter deposits (Moore, 1983). This change in topographic expression corresponds to a transverse structural break (Figure 4). It is also the site of the geothermal resource discovery Well HGP-A. Underlying the surface expression of the rift at a depth of generally 7600 feet below the surface, is a much broader (5-15 miles wide) dike complex defined by Furumoto (1978). This dike complex is thought to consist of a dense aggregate of closely spaced, parallel to subparallel, vertical to steeply dipping dikes. The intervening region between the dike complex and surface expression of the rift is considered transitional with respect to dike density (Figure 3). The dikes intrude both Mauna Loa and Kilauea lava flows. The dike complex is reported by Furumoto (1978) to be locally above the Curie Point (1000°F) and in places, may even approach the melting point of basalt (1900°F). Petrologic studies of lavas in the rift indicate the presence of differentiated tholeiite which strongly suggests the existence of secondary magma chambers. The Puna geothermal system overlies such an area (Moore, 1983).

A generalized geohydrological model from the east-trending rift zone of Mauna Kea through the LERZ to the sea and the Ghyben-Herzberg principal, are depicted in Figures 2a and 2b, respectively. Basal water occurs north and south of the rift. Within the rift, however, the Ghyben-Herzberg principal is not thought to apply and the water is considered dike-controlled[2] (Figure 2a) because of the strong structural constraint on water flow imposed by the rift (e.g., dikes, faults). Dike-impounded (or dike-confined) water occurs within the rift zone typically at high elevations where water levels are encountered hundreds of feet above mean sea level. At lower elevations, water within the rift is approximately at sea level.

1 Utilized in this study are all available geotechnical data, statistical and pattern recognition techniques and set theory. Analytical conservatism is maintained throughout the analysis.

2 The term dike-controlled is credited to Mr. D. Fraim of Hawaii Department of Health whose valuable discussions on the hydrology of the Hawaiian Islands assisted the preparation of this document.

Potential freshwater recharge in the LERZ is thought to be derived from both the area uprift of the PGV-PA, (Figure 1) and local rainfall through infiltration. Annual rainfall in LERZ is about 120 inches. This water immediately infiltrates into the ground as virtually no standing water bodies exist. A secondary source of potential recharge to the LERZ is Mauna Loa to the north and northwest. Flow from this large, volcanic edifice would undoubtedly be ponded against the impermeable, northern boundary of the rift. Water would percolate into and through the rift zone only along relatively discrete high permeability sections (e.g. faults) and/or by physically overflowing the dikes. The East Rift Zone forms an excellent barrier to groundwater flow (Druecker and Fan, 1976; Imada, 1984). Groundwater residence time in the LERZ, reported by Kroopnick et al (1978), is on the order of years. The high annual rainfall and short residence time evidence a vigorous groundwater flow system.

barrier to flow in what direction?

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Seven deep exploratory wells have been drilled to date where the east-northeast trending rift zone has been structurally offset by a north-northwest trending transverse fault (Figure 4). The geothermal system is thought to be localized by this major fault intersection. Four of the seven wells have been successful. A conceptual model of the principal elements of the geohydrologic setting of the Puna geothermal system is presented in Figure 3. Briefly, the Puna reservoir is a very high temperature, greater than 600°F, two-phase liquid dominated system containing a varying steam fraction and is rift confined except where broken by faults. The reservoir is maintained in this thermodynamic state by a very high heat flow within the rift and by an effective seal inhibiting significant venting of the reservoir to the surface. In spite of the tremendous heat flux generated by the rift zone environment, no marked geothermal surface manifestations (e.g., Yellowstone type) are present except for several hot springs discharging along the southeastern coast of the Big Island of Hawaii and for isolated steam vents within the rift which appear to be more closely related to recently active fissures. The lack of surface manifestations is attributed to a vigorous, cool groundwater system which "hydraulically masks" the geothermal reservoir and a relatively impermeable seal around the reservoir. This coupling effectively keeps the geothermal reservoir suppressed. Where the seal is locally broken by structure, however, leakage of geothermal fluids does occur. Leakage should diminish over time by mineralogical self-sealing of the permeable structures unless reoccurring fault movement maintains these fluid conduits. While this self-sealing phenomenon does occur in a geologic time frame, it will be shown that currently, geothermal fluid leakage from the reservoir into the shallow and intermediate level ground water system is sufficient to totally alter its original fresh water character.

Hydrochemistry

Cox and Thomas (1979) conducted a chemical review of some 400 groundwater samples in the State of Hawaii and have determined three parameters which identify the presence of geothermal water: temperature in excess of 84°F, chloride to magnesium ratio (Cl/Mg) greater than or equal to 15, and silica content exceeding 30-85 mg/l depending on locality. Their study provides the chemical basis for this review.

The location of all the wells[3] in the LERZ are presented in Figure 4 along with selected, key hydrochemical parameters:

1. Total dissolved solids content,
2. Water level,
3. Temperature,
4. Cl/Mg, and
5. SiO_2 content.

Physical data on these wells and their available water chemistry, are summarized in Tables 1 and 2, respectively. Table 1 indicates that the chemical well data pertains to the top of the basal water north and south of the rift. Within the rift, it applies to the top of the dike-controlled water. The only unequivocal exception is Well HGP-A (Table 2) which corresponds to the intermediate level groundwater system. The location, depth and chemistry of Well 9 suggests that it is producing from a perched aquifer. Although a relatively small number of wells (i.e. only 16 data points) exist, regional geohydrochemical systematics are evident which impart critical insights to the injection regulation issue.

how? inferred.

North of the LERZ, groundwater elevations would suggest groundwater flow in a north-south direction towards the ocean. However, given the limited data available, it is inferred that a significant portion of the flow in this area is actually moving to the northeast following the topography of Mauna Loa and the LERZ (Figure 4). Within the LERZ, minor dike impoundment has been reported by Kauahikaua et al (1980) and is also observed most notably in Well KS-1A (Table 1). Water flow is principally parallel to the rift (Takasaki and Mink, 1985). South of the LERZ, groundwater elevations do not show a consistent pattern. Groundwater probably flows in a southerly to southeasterly direction following topography towards the ocean.

Maximum water temperature in the LERZ wells indicate that ambient conditions exist to the north. Elevated temperatures are present throughout the rift zone except for Well 9 at Kapoho Crater. This well at the base of the Kapoho Crater taps water from an ash formation (Davis and Yamanaga, 1968). It is believed that much of its flow is derived from Green Lake located up gradient within the crater which is the only standing body of water in the entire LERZ. Its existence is attributed to the ash layer acting as an aquitard. Water flow from Green Lake into Well 9 is interpreted to alter both the well's true temperature and chemical characteristics. Wells south of the LERZ show variable temperatures with significantly greater than ambient temperatures south and southeast of the PGV-PA (Figure 4).

The selected hydrochemical data illustrated in Figure 4 and the detailed water chemistry for these wells presented in Table 2 evidence a variability on both an individual well basis (e.g., Well 9-9a through 9-9e, Table 2) and on an areal basis (e.g., Wells KS-1, KS-1A, KS-2 and GTW-III, Figure 4). These data represent analyses conducted by different State and Federal agencies at different times. The variations can be attributable to:

3 The term well is broadly applied herein to also include shafts, holes, etc.

(1) different sampling procedures,

(2) different analytical methods,

(3) environmental factors affecting the water chemistry of the samples such as a significant rain fall prior to sample collection,

(4) natural variations in water chemistry, and

(5) some combination of the above.

Schoeller diagrams (vertical scale chemical concentration plots) have been used to evaluate the validity of individual well, multiple chemical data (Appendix A). Except for Well 9 which displays at least two distinct waters chemistries, the chemical data are in general, coherent and most likely reflect dilution/concentration effects related to the dynamics of the geohydrochemical setting. Significant sampling and/or analytical errors are not evident. Although variability exists on an areal basis, a consistent geochemical pattern has been detected which distinguishes fresh water from geothermal water.

Figure 5a is a semi-logarithmic frequency distribution diagram of the total dissolved solids (TDS) content for wells from the LERZ. TDS content is utilized as it reflects the gross chemical character of the water. Included in this figure are data from four fresh water drinking wells on the island of Oahu (Table 3) which provide an independent, internal control set. The TDS plot has been coded for the three principal indicators of geothermal waters reported by Cox and Thomas (1979): temperature (Figure 5b), chloride to magnesium ratio (Figure 5c) and silica content (Figure 5d). Conservatively, it is observed that all wells with a TDS content greater than 2000 mg/l, exhibit Cl/Mg ratios in excess of 15 and a temperature greater than or equal to 100°F. An elevated temperature of 100°F and chemical signatures clearly fingerprint a water as geothermally anomalous. The silica content of these waters (Figure 5d) displays a more ambigious pattern. This is attributed to not only the data variation factors described above but also to some extent, precipitation reactions lowering the silica content of the geothermal waters. This four-parameter analysis provides a basis for discriminating betwen wells which contain either fresh or geothermal water (Table 4).

An independent validation of water type is made through the utilization of 13 chemical parameters given in Table 2. Consistent relationships observed upon increasing the number of parameters involved in any single analysis is interpreted to reflect a meaningful geologic phenomena. It is postulated that unique geothermal and fresh water Schoeller Diagram patterns exist. To evaluate this, the chemical data for any well which occurred in two out of the three geothermal water categories listed in Table 4 were plotted in Figure 6. In contrast, all three fresh categories for fresh waters in Table 4 had to be satisfied before being plotted (Figure 7) for analytical conservatism. Data for Wells 9a, 9b, 9-6a and 9-6b (Table 4) were not plotted in Figure 7 for the following reasons. Well 9 shows at least two distinct fluids, a a Na-Ca-HCO_3 and Na-Cl-SO_4-HCO_3 type. Imada (1984) reports that the high bicarbonate (HCO_3) of the fluids results from volcanic emanations. Perched water in Puna, Hawaii tends to be of either a Na-Ca-HCO_3 or a Na-Mg-HCO_3 type; while basal waters are predominately Na-Cl (Druecker and [illegible], 1976). The physical setting of Well 9 is consistent with a perched [illegible]fer origin. Well 9-6 exhibits temperature approximate to 100°F and one of the hotter samples 9-6c also shows a Cl/Mg ratio greater than 15.

PUNA GEOTHERMAL VENTURE
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Reference No.: 90088 Date: February 13, 1989 Page 1 of 1

To: Mr. James Moulds
Company:

From: M. Richard
CC:

We are sending via (XX) mail ( ) facsimile ( ) other
(XX) attached ( ) under separate cover

(XX) for your information/files ( ) approval ( ) as requested
( ) review and comments ( ) as discussed ( ) action
( ) signature and return ( )

RE:

Copy of the Geotechnical Report dated July 3, 1986.

Comparison of Figures 6 and 7 illustrates that fresh water can be chemically differentiated from geothermal waters, significantly enhancing the previous conclusions. The geothermal fluid contains markedly higher concentrations than fresh water for most of the ions reviewed. They are also anomalous in Mg, SiO_2, HCO_3 and Cl content, Cl/Mg ratio and pH as shown in Figure 8 which illustrates the chemical relationship between geothermal and fresh waters if the concentration effect in the geothermal waters is reduced by one order of magnitude.

These results allow the characterization of three water types: geothermal, mixed and fresh for wells in the LERZ (Table 5). To maintain analytical conservatism, geothermal waters were only designated upon clear, overwhelming evidence. The temperature and chemical signatures observed in KS-1, KS-1A, KS-2, and GTW-III within the rift and 9-9 and A south and southeast of the rift (Figure 4) are interpreted to result from relatively direct leakage of geothermal fluid into the dike-controlled and basal waters, respectively. The major fault intersection is considered the principal cause for upwelling of geothermal fluids from the geothermal reservoir located in the deep subsurface. This postulation is corroborated by the spontaneous potential anomalies identified by Zablocki (1977). Well 9-9 is proximal to the transverse fault. Well A is a considerable distance away from this feature and its diluted water chemistry and reduced temperature is consistent with mixing of geothermal fluids with fresh water. Previous studies (Davis and Yamanaga, 1968 and 1974; Druecker and Fan, 1976; McMurtry et al, 1977; and Imada, 1984) attribute the saline nature of the waters south of the LERZ to be the result at least in part, to a decrease in recharge rate to the basal water. The temperature anomaly clearly identifies the geothermal character of these waters. Wells 9-6 and GTW-IV are a mixed water type because they display a partial geothermal character. These wells occur within the LERZ down the hydrologic gradient from the primary identified area of geothermal fluid upwelling. It is postulated that geothermal fluids migrating down the rift mix and possibly react with fresh water resulting in the modified chemical signature. It is also possible that upward leakage of geothermal fluid is also occurring immediate to 9-6 and GTW-IV but to a much lesser extent than in the primary area. Well 9 is also considered a mixed water type for reasons discussed above. Only Wells 9-5 and 9-7 located north and southwest, respectively of the primary area of geothermal fluid upwelling, unambiguously contain fresh water.

This characterization, while specific to the top of the basal water or dike controlled water in the LERZ (shallow subsurface), is also directly applicable to the intermediate subsurface. However, the paucity of data on the intermediate depth geohydrochemical system, limits a detailed review. Figure 9 shows that as expected, the total dissolved solids content of the water in the LERZ and temperature are proportional. Wells HGP-A, KS-1, KS-1A and KS-2 have all been found to increase in temperature with depth. It can be readily expected that with increasing depth and temperature, the geothermal character of the water will be progressively enhanced until the geothermal reservoir itself is intersected. The intermediate subsurface in the area of Well 9-9 and to a greater extent Well A, may not contain geothermal waters. This would depend upon the specific degree and depth location of geothermal fluid upwelling in that portion of the structural intersection outside of the rift (Figure 4).

HDOH, UIC REGULATIONS

Classification of exempted aquifers and Underground Sources of Drinking Water, Section 11-23-04 of the HDOH, UIC regulations is presented in Appendix B. Each criteria listed to classify exempted aquifers, is given below in bold type and reviewed for its applicability to the PGV-PA.

(1) The aquifer does not currently serve as a source of drinking water.

The only wells clearly containing fresh drinking water in the LERZ are 9-5 and 9-7 located to the north and south, respectively of the Rift. Furthermore, Well 9-7 is considerably southwest of the area of primary geothermal fluid leakage and oblique to the hydrologic gradient.

(2) The aquifer cannot now and will not in the future serve as a source of drinking water because of any of the following criteria:

(a) it is situated at a depth or location which currently makes recovery of water for drinking water purposes economically or technologically impractical; or

(b) it is so contaminated that it would be economically or technologically impractical to render that water fit for human consumption; or

(c) the total dissolved solids (TDS) concentration of the groundwater is more than five thousand mg/L, and it is not reasonably expected to supply a public or private drinking water system.

Waters in the PGV-PA and to the south and southeast Wells 9-9 and A are clearly geothermal in character (see Figures 1, 4 and Table 5). Mixed water types exist down the hydrologic gradient from the area of primary geothermal fluid. The East Rift Zone is not the typical geologic setting for drinking water in the State of Hawaii. Geothermal waters are considered economically and technologically impractical to render water fit for human consumption. Mixed waters are considered marginal for drinking water. There also exists a high probability that any well containing a mixed fluid type may entrain a greater geothermal component to its fluid under high flow rate conditions.

(3) The UIC maps shall indicate exempted aquifers and USDW, in plan view, by use of a UIC Line, and such maps are an integral part of this chapter. The department's UIC maps shall be the final authority for the identification of the aquifer boundaries on the land surface.

The PGV-PA, as well as, the entire LERZ is mauka (towards the mountain) of the existing HDOH, UIC line. The UIC line should be modified to include that area of the LERZ when geothermal and mixed waters are identified.

(4) Unless expressly exempted, all aquifers are considered to be USDW.

A large region within the LERZ satisfies criteria (1) and (2) in HDOH, UIC rules, Section 11-23-04, given above.

CONCLUSIONS AND RECOMMENDATIONS

The geohydrochemical review of the shallow and intermediate subsurface in the LERZ of Kilauea Volcano, Hawaii, Hawaii indicates:

(1) fresh water can be thermochemically differentiated from geothermal waters,

(2) wells containing geothermal waters occur in the proximity of a major structural intersection in the LERZ,

(3) upwelling geothermal fluids from the geothermal reservoir in the deep subsurface are interpreted to be taking place along the zone of structural intersection,

(4) geothermal fluid leakage from the reservoir is sufficiently strong to overwhelm the character of fresh water in the zone of vigorous groundwater flow,

(5) mixed water type wells evidence the dynamic nature of the geohydrological setting,

(6) the East Rift Zone is not a typical geologic setting for drinking water in the State of Hawaii,

(7) the area of primary geothermal fluid leakage both within and outside the rift as well as the area hydrologically downgradient should be withdrawn from the classification of underground sources of drinking water.

It is recommended that the UIC line be modified as shown in Figure 10. The modified line encompasses the Kapoho Geothermal Subzone designated by the Board of Land and Natural Resources under Act 296, SLH 1983, as well as Wells 9-9 and A south and southeast of the PGV-PA. Modified UIC line is consistent with the purpose and scope of HDOH, UIC regulations. The observation that the intermediate subsurface in the area of Wells 9-9 and A (Figure 10) may not contain geothermal waters does not impact the petition to modify the UIC line as discussed. The reason for this is that the UIC line only describes where injection can occur in a horizontal dimension. The vertical dimension is regulated by Section 11-23-05 of the HDOH, UIC regulations (Appendix C).

OTHER CONSIDERATIONS

The existence of an GEA defines the exempted aquifer area in a horizontal dimension. The vertical dimension is regulated by Section 11-23-05 of the HDOH, UIC regulations (Appendix C).

Mr. Fraim of HDOH has informed Thermal Power Company (personal communication, May 1986) that the occurrence of water in the LERZ is non-artesian. As a consequence, the entire geologic column in a vertical dimension is treated as an exempted aquifer.

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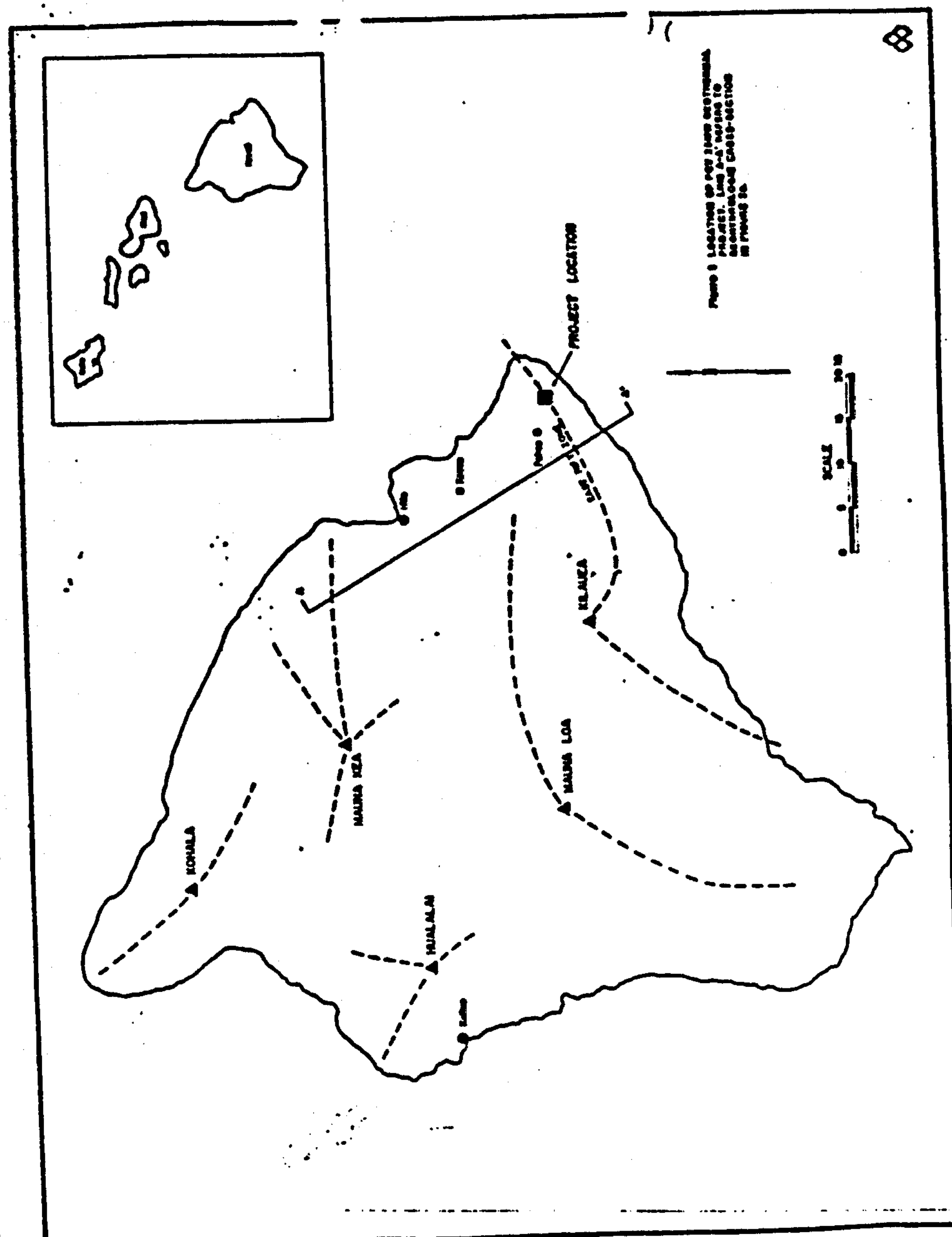
RECJLI



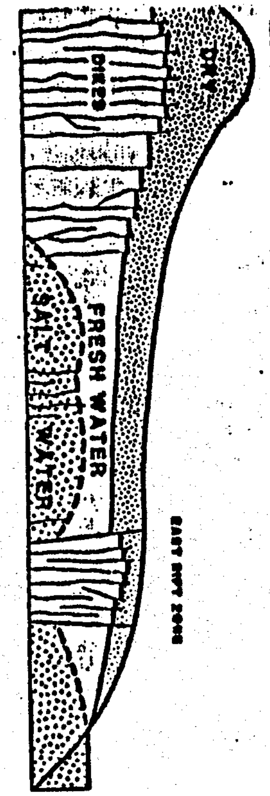
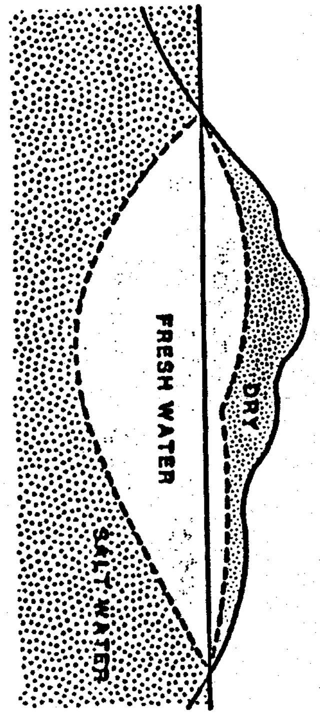


Figure 2a Schematic cross-section from the rift zone of Mauna Kea through the East Rift Zone of Kilauea (see Figure 1) showing the distribution of fresh water and salt water (modified after Stearns and Macdonald, 1946). Two types of ground water occurances are illustrated: dike-controled and basal water (Figure 2b) within and outside the rift zone, respectively. Only two water chemical categories are shown.

2a

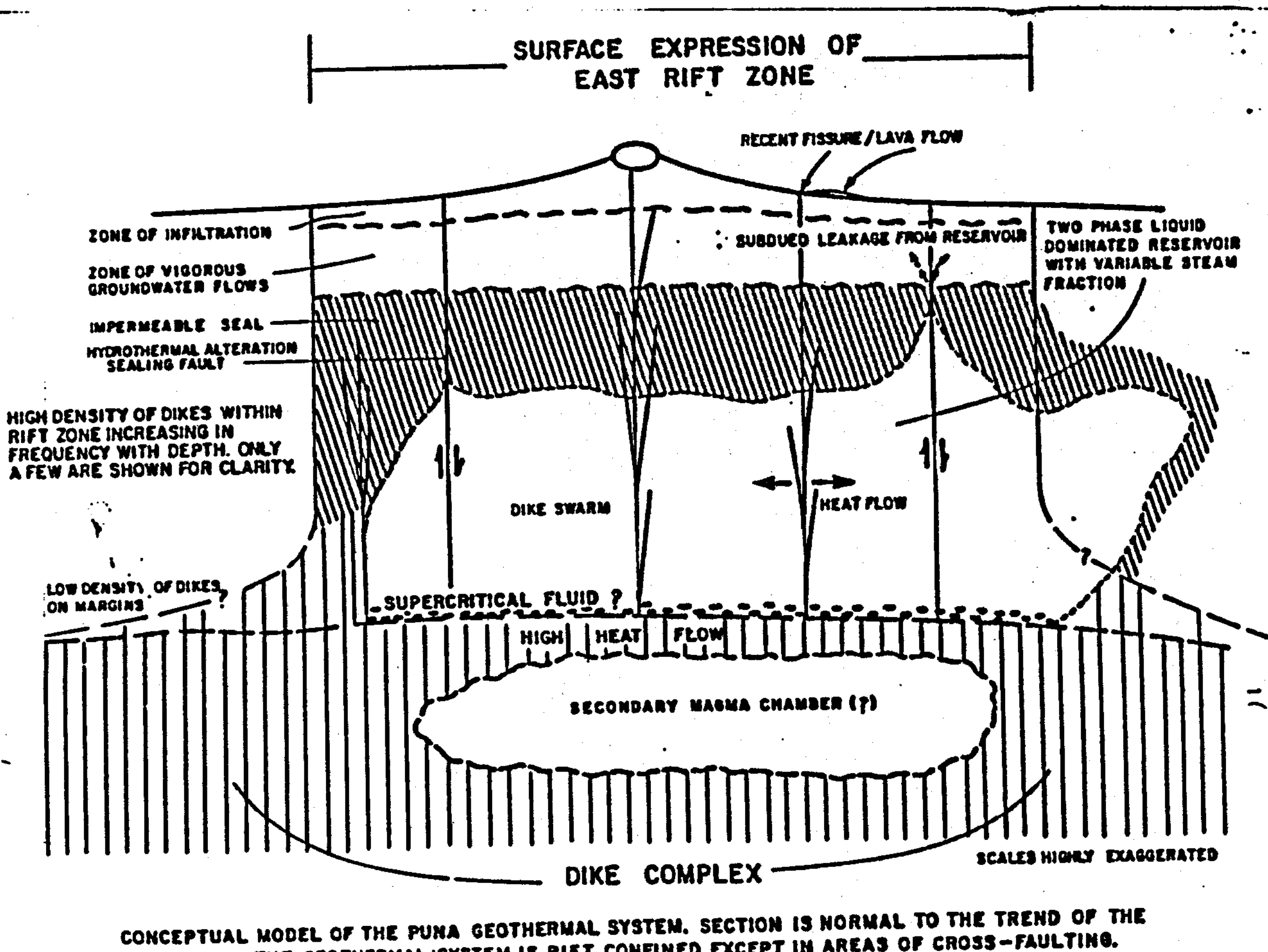


2b

Figure 2b The Ghyben-Herzberg Principle showing the lens of fresh (basal) water floating on salt water (modified after Stearns, 1946).

GENERALIZED MODEL OF THE GEOHYDROLOGIC SETTING OF THE EAST RIFT ZONE.

Fig 2



CONCEPTUAL MODEL OF THE PUNA GEOTHERMAL SYSTEM. SECTION IS NORMAL TO THE TREND OF THE RIFT ZONE. THE GEOTHERMAL SYSTEM IS RIFT CONFINED EXCEPT IN AREAS OF CROSS-FAULTING. IMPERMEABLE SEAL IS THOUGHT TO BE DUE TO LITHOLOGY AND HYDROTHERMAL ALTERATIONS.
Figure 3

Fig 3

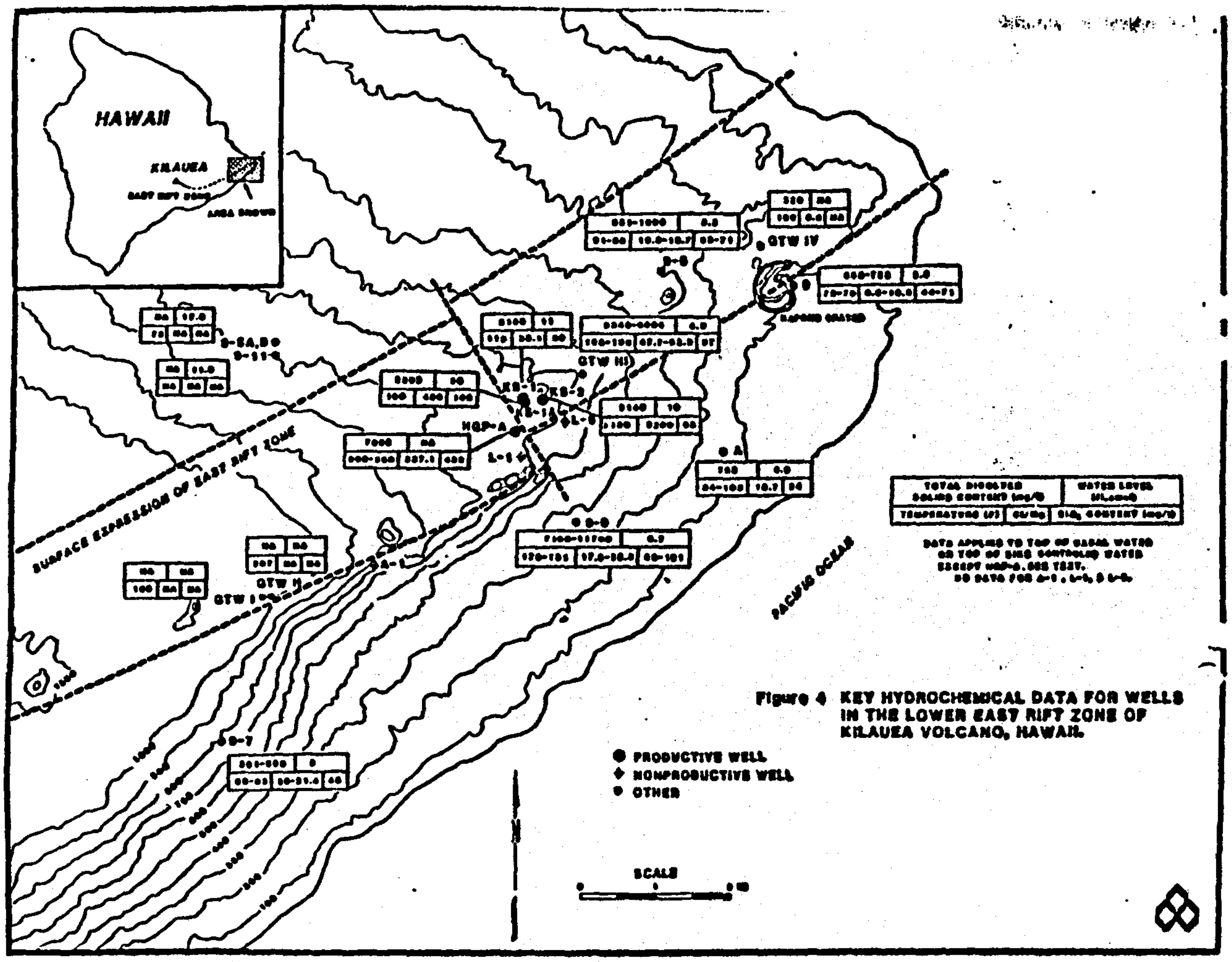


Figure 4 KEY HYDROCHEMICAL DATA FOR WELLS IN THE LOWER EAST RIFT ZONE OF KILAUEA VOLCANO, HAWAII.

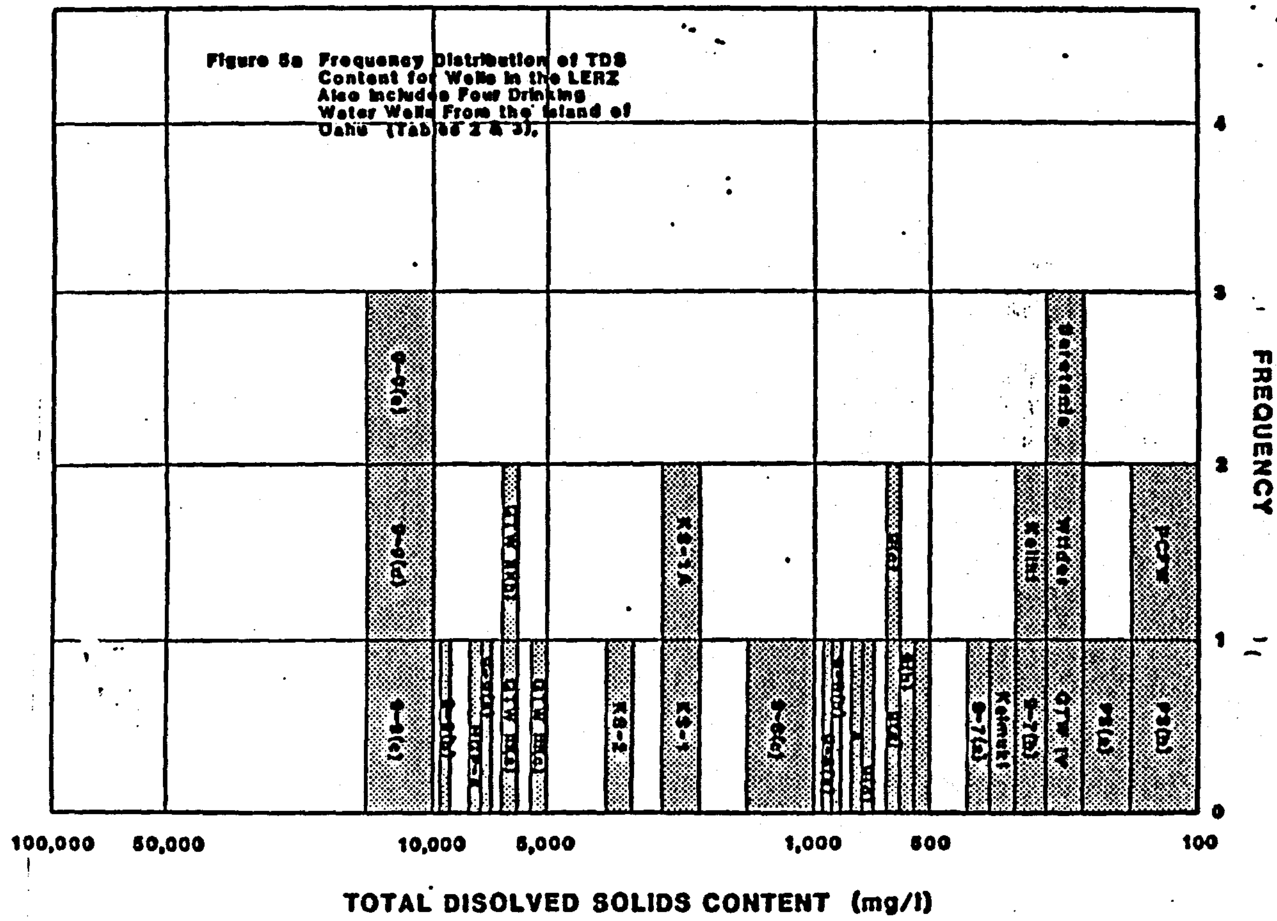


Figure 5a Frequency Distribution of TDS Content for Wells in the LERZ Also Includes Four Drinking Water Wells From the Island of Oahu (Tables 2 & 3).

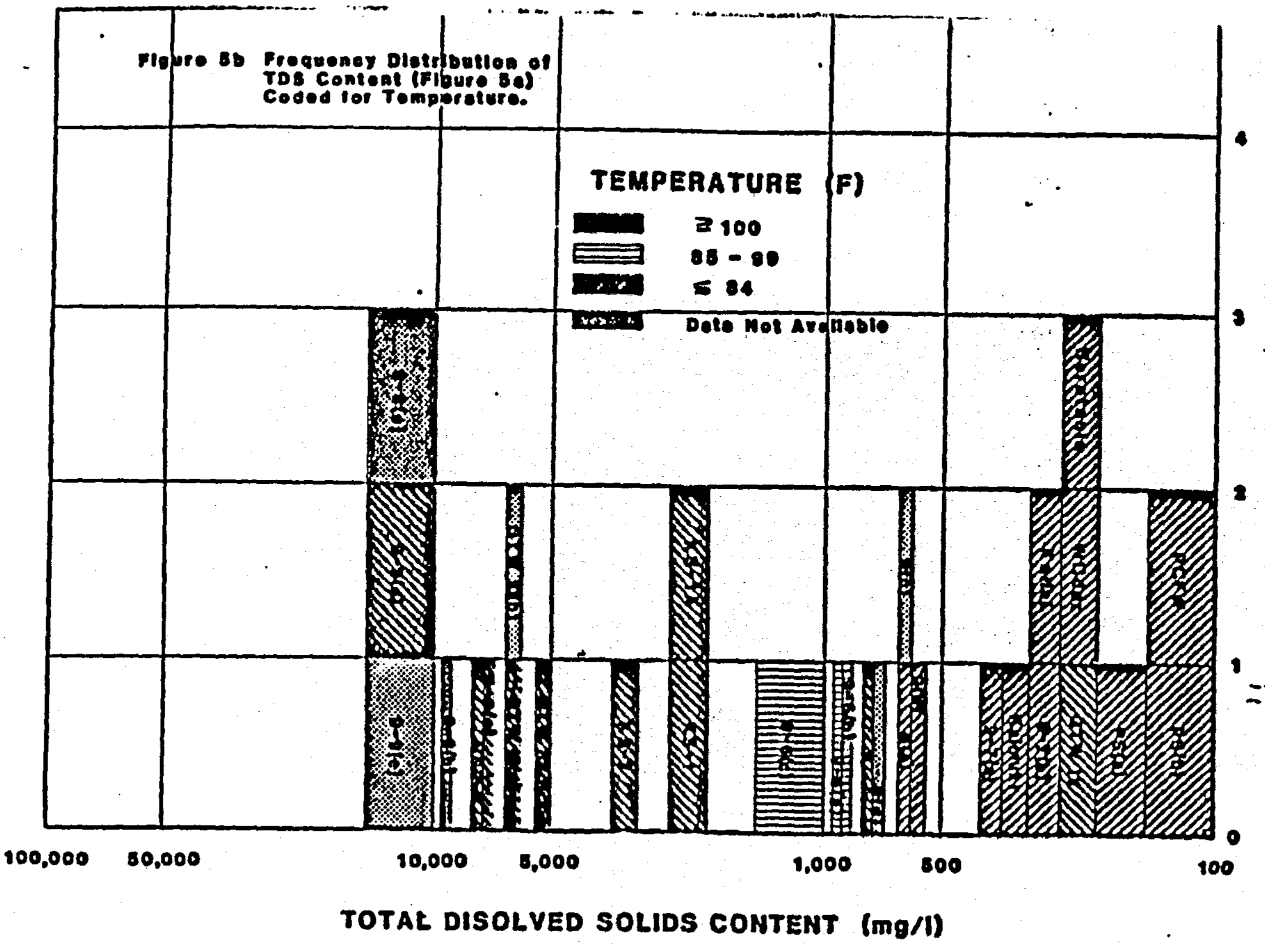


Figure 5b Frequency Distribution of TDS Content (Figure 5a) Coded for Temperature.

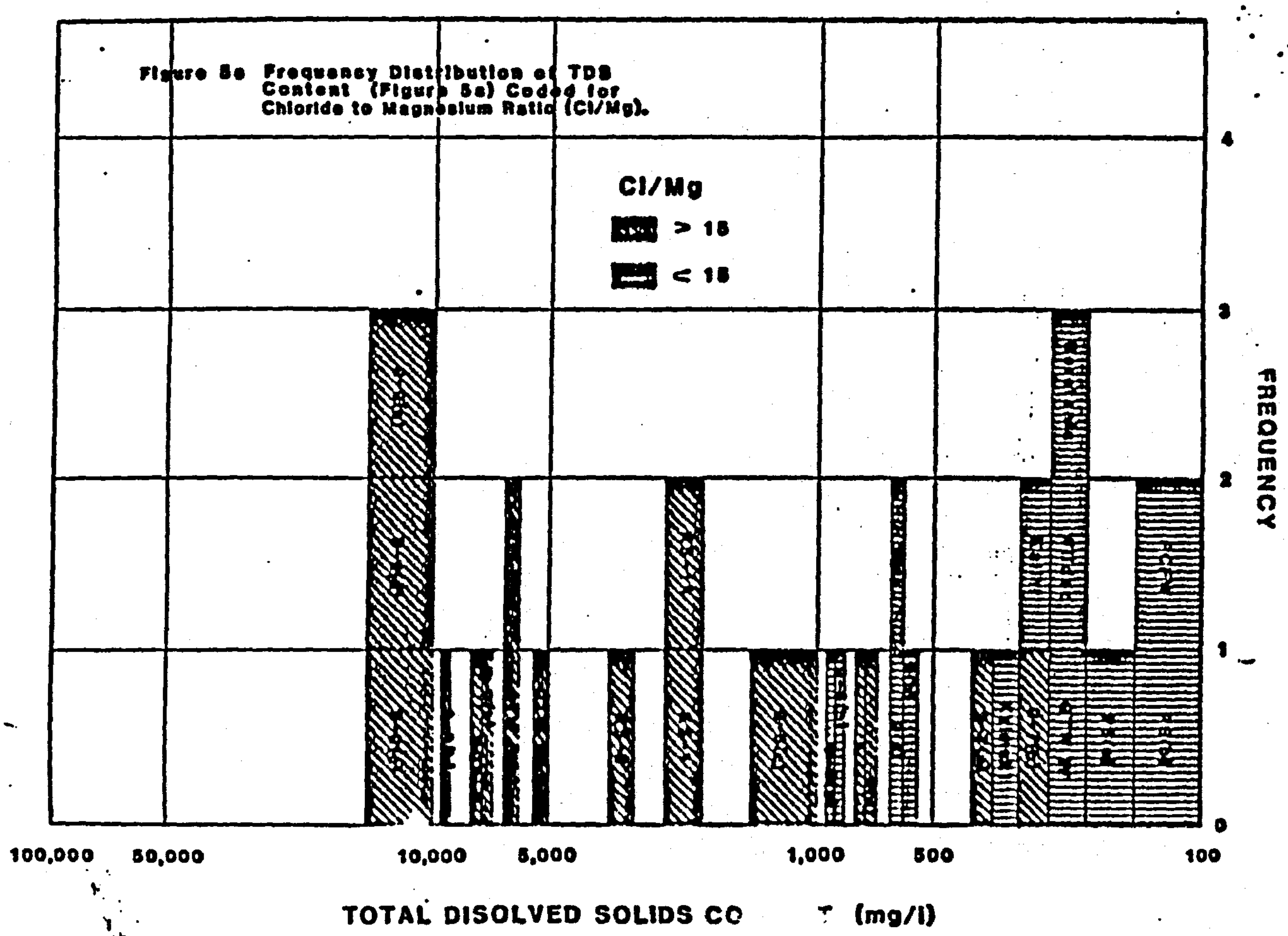


Figure 5c Frequency Distribution of TDS Content (Figure 5a) Coded for Chloride to Magnesium Ratio (Cl/Mg).

Figure 5d Frequency Distribution of TDS Content (Figure 5a) Coded for Silica (SiO_2) Content.

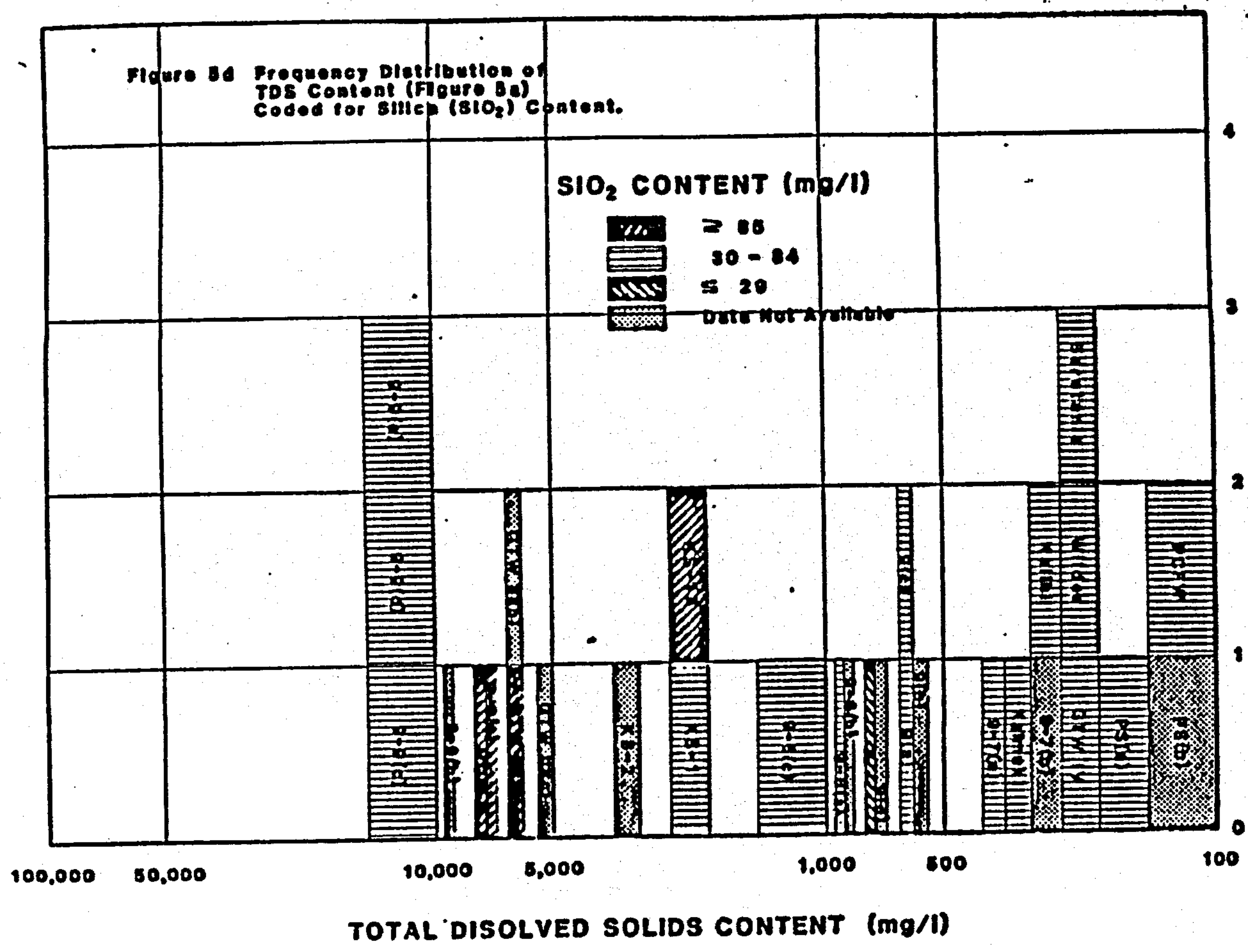
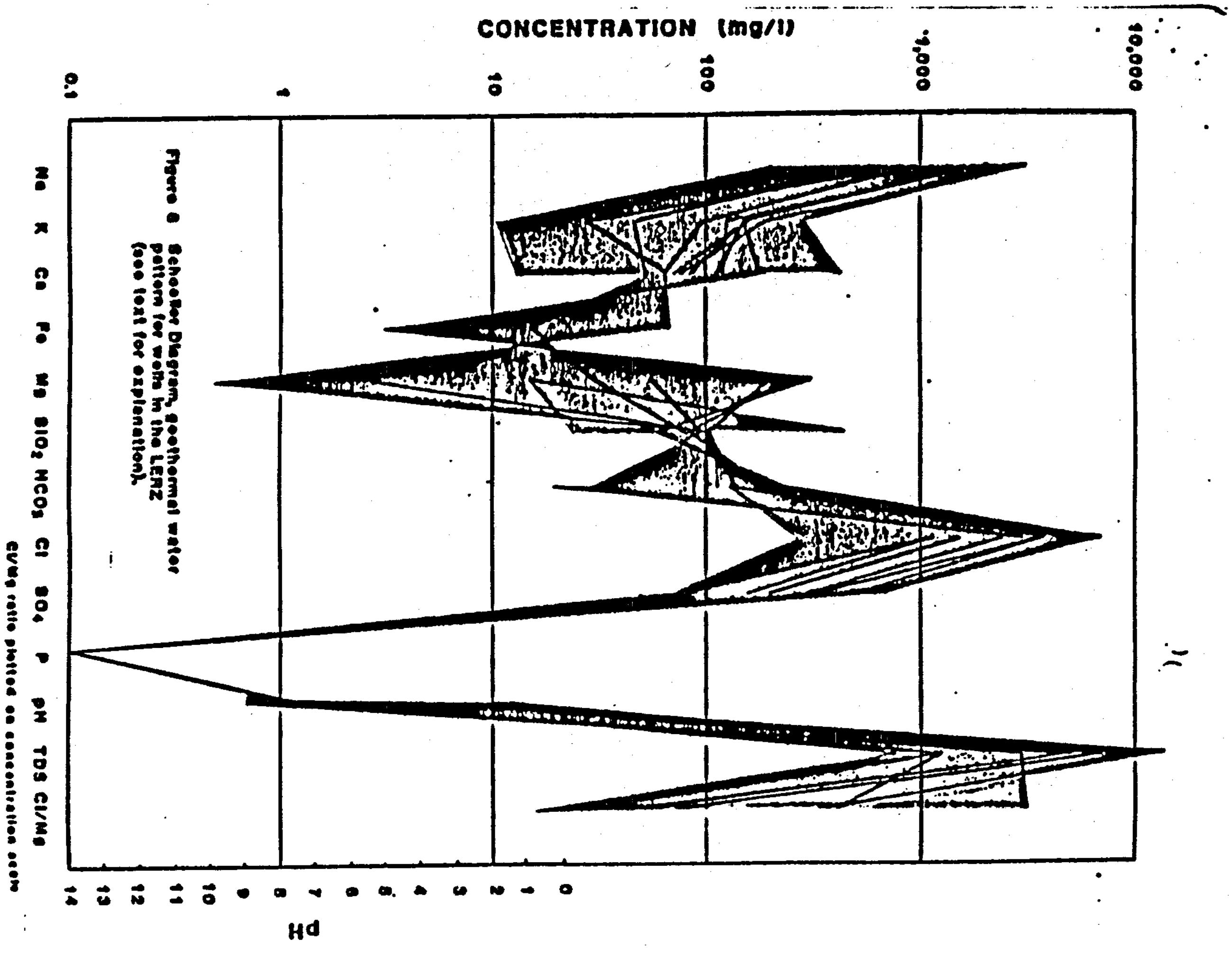


Figure 6 Schoeller Diagram, geothermal water pattern for wells in the LERZ (see text for explanation).



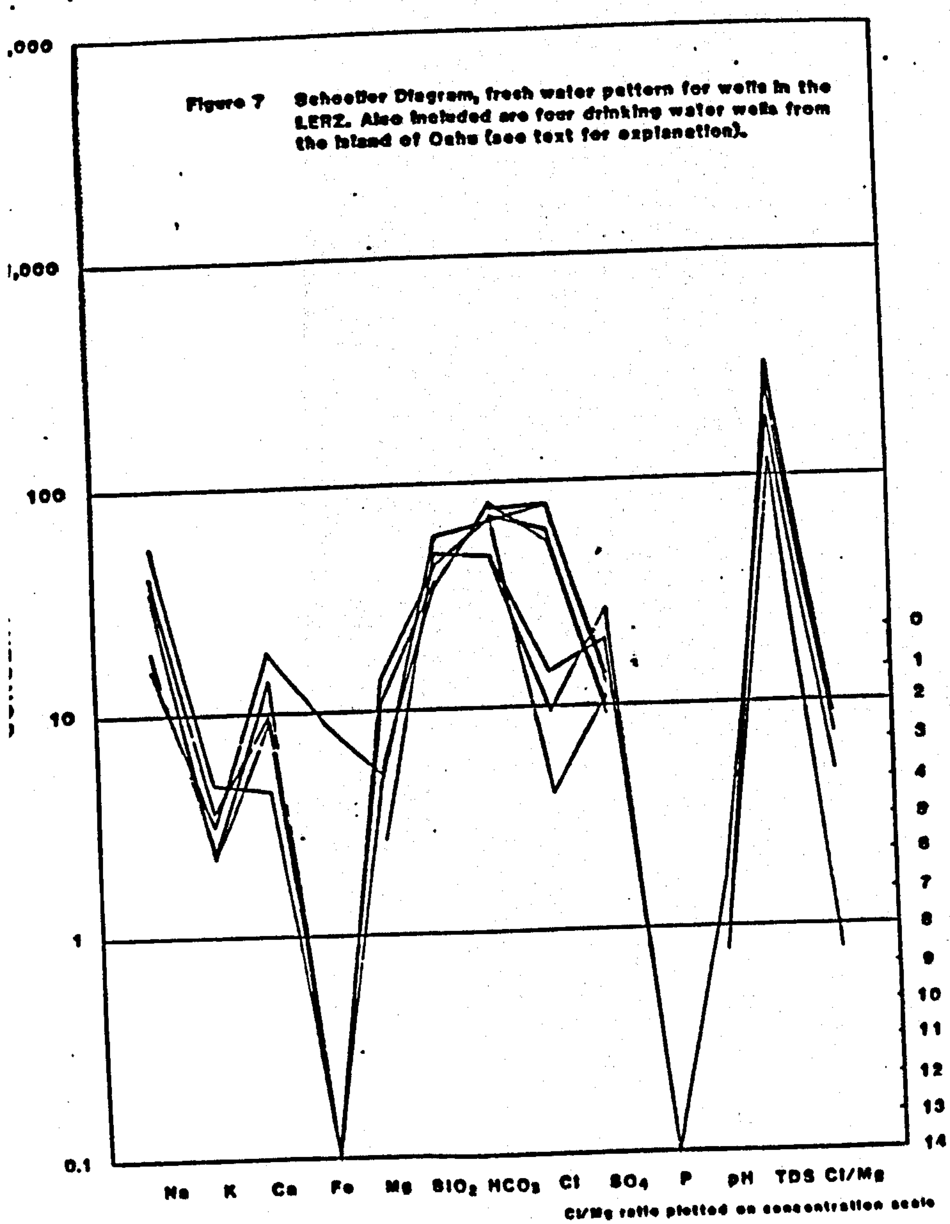


Figure 7 Schoeller Diagram, fresh water pattern for wells in the LERZ. Also included are four drinking water wells from the island of Oahu (see text for explanation).

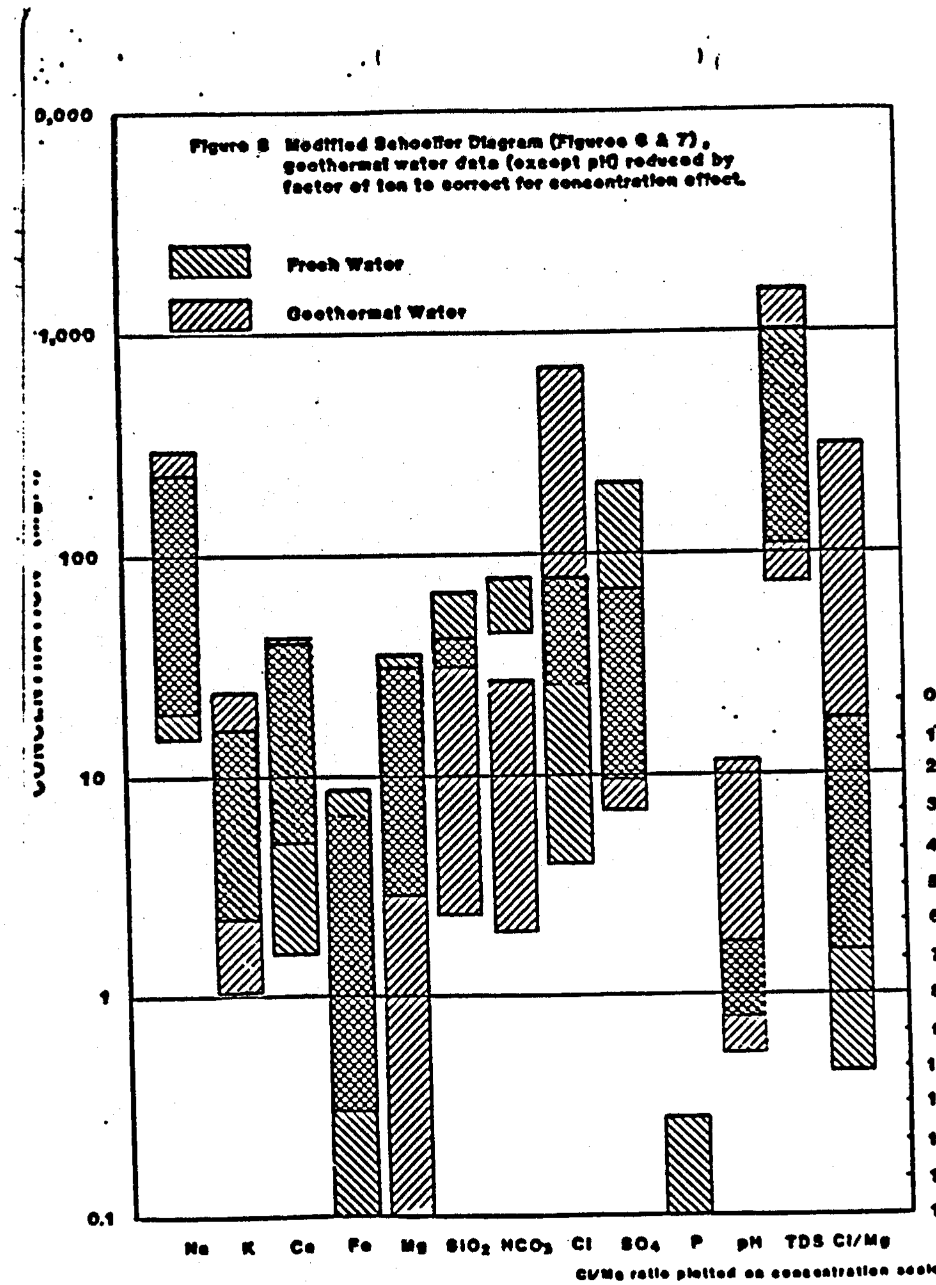


Figure 8 Modified Schoeller Diagram (Figures 6 & 7), geothermal water data (except pH) reduced by factor of ten to correct for concentration effect.

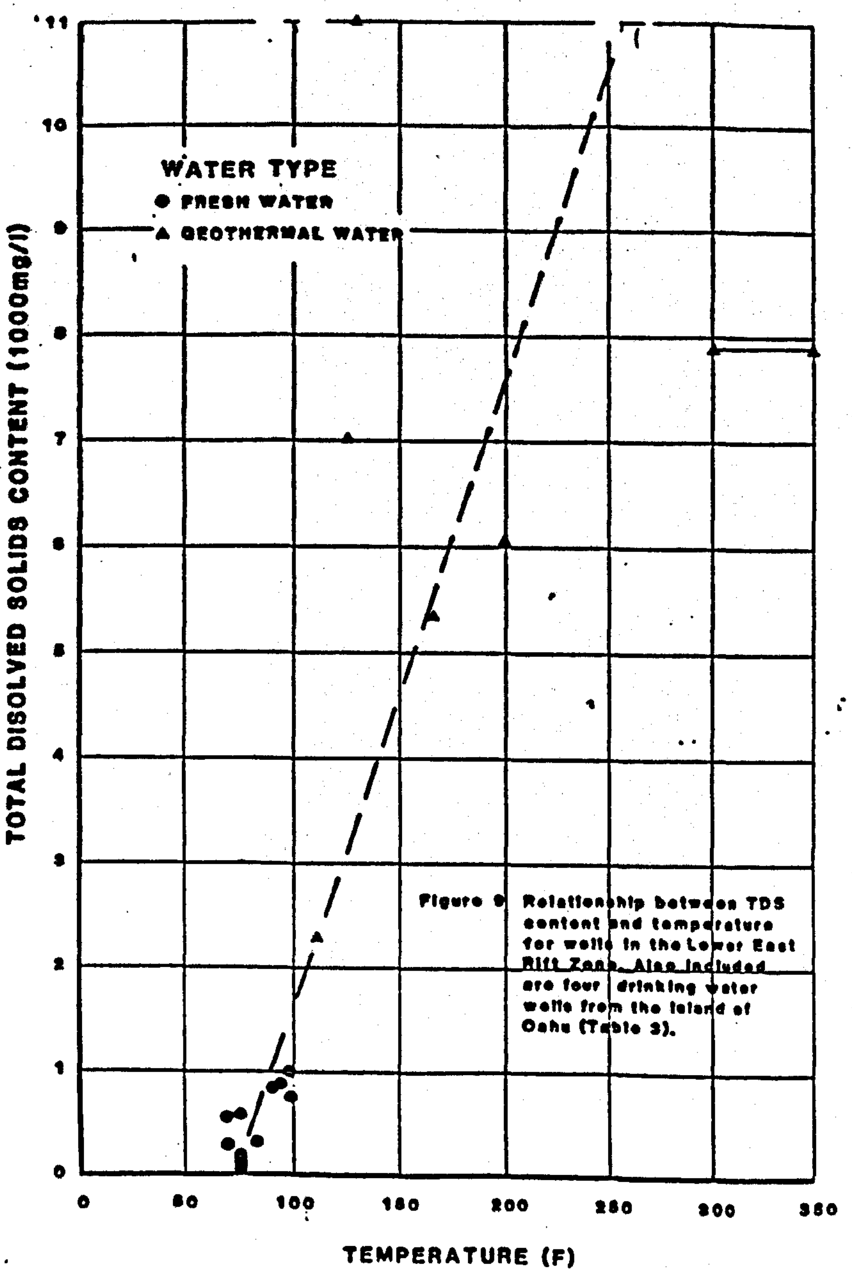


Figure 9 Relationship between TDS content and temperature for wells in the Lower East Rift Zone. Also included are four drinking water wells from the island of Oahu (Table 3).

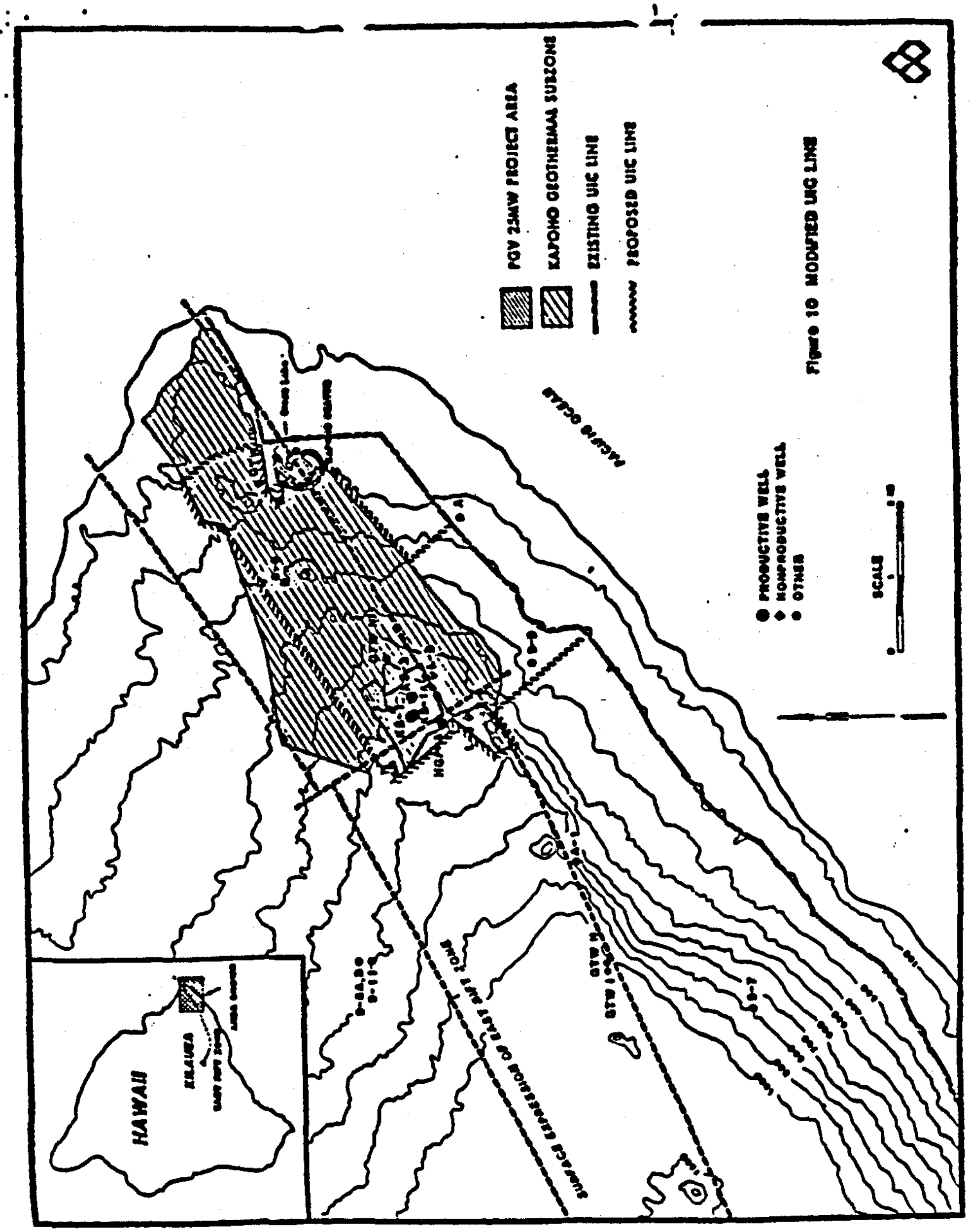


Figure 10 MODIFIED UIC LINE

Table 1. Physical data on wells[1] in the LERZ. See Figure 4 for location. Data from Epp and Halunen (1979), Weiss Associates (1983) and Thermal Power Company.

Well	ELEVATION (ft., amsl[2])	DEPTH (ft.)	WATER LEVEL (ft., amsl)	MAXIMUM TEMP. (°F)	
9-5 A	705	754.7	17.8	72	North of Rift
9-5B	NA	NA	NA	NA	
9-6	287	337.15	3.3	98	
9-7	752	801.9	2.94	73*	
9-9	274	316	0.7	131*	
9-11	402	446	11.6	72	North of Rift
9	38	41	2.6	77	
A	129	140	4.9	102*	
GTW-III	563	690	4.9	199	
GTW-IV	250	290	NA	109	
KS-1	617	782***	11	113	
KS-1A	617	586***	38**	NA	
KS-2	718	732***	10	NA	
GTW-I	1009	178	NA	156	
GTW-II	1035	556	NA	207	

1 The term is loosely applied to also include shafts, holes, etc.

2 Above Mean Sea Level

* Temperatures reported in Table 2 are 69° and 83°F for well 9-7, 126°-128°F for well 9-9, and 100°F for well A.

** The significant differential in water level between KS-1 and KS-1A (Figure 4) is in part, thought to result from a data collection error.

*** Depth of well when formation water was intercepted.

Table 2. Water chemistry for wells in the LERZ. All data is in mg/l unless otherwise indicated. See Figure 4 for locations; no data is available on geothermal wells A-1, L-1, and L-6. The term wells for the purposes of this report also includes shafts. Data source is listed below.

WELL

Parameter	PSa	PSb	PVFW	KS-1	KS-1A	KS-2	HGP-A	GTW-III-a	GTW-III-b	GTW-III-c	9-6a	9-6b	9-6c	GTW-IV
Temp(°F)	75	74	75	113	>100	>100	300-350	199	N.A.	163	91	92	96	N.A.[b]
pH	7.3	6.65	8.5	N.A.	8.5	9.5	3	6.85	N.A.	1.4	7.42	7.75	7.1	7.9
Na	36.0	19.3	16	614	921	1000	2008	2050	2000	1740	238	223	231	49.2
K	2.72	2.7	3.3	46.1	26.0	94	245	190	195	158	13.6	16.8	15.2	
Ca	1.58	1.6	19	53.2	65.8	65	445	76.8	81	71	23.0	12.5	16.5	16.2
Mg	2.7	1.9	5.1	30.2	2.71	0.5	14	52	59	62.5	28	27.2	24.1	7.5
Cl	13.5	9.8	4	1150	1098	1600	4720	3274	3410	2980	303.5	316	450	72
SO_4	48	44	11	169	74	210	N.A.	314	335	317	204	211	106	18.4
HCO_3	21.1	27.3	71	N.A.	N.A.	N.A.	N.A.	30	N.A.	20	48	44	46	N.A.
SiO_2	50.0	N.A.	62	80	104.6	93	432	96.6	N.A.	N.A.	71.3	N.A.	63	44
F	0.08	0.13	N.A.	N.A.	N.A.	N.A.	N.A.	.006	.076	0.033	0.04	0.076	N.A.	N.A.
Fe[a]	N.A.	N.A.	8.8	15	N.A.	70	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.2	.1
TDS	176	107	120	2158	2292	3140	7865	6084	6080	5349	929	851	1006	220
Cl/Mg	5.0	5.16	0.78	38.08	405.17	3200	337.14	62.96	57.8	47.68	10.8	11.6	18.67	9.6

PSa	Pahoa Station, 6 Jan. '75 sample from Water Resources Research Center (WRRC), University of Hawaii, Manoa (UH-M).
PSb	Pahoa Station, 21 July '75 sample from WRRC, UH-M.
PVFW	Pahoa Village Fresh Water, October 1985, sample from Thermal Power Company.
KS-1	Geothermal Well, Kapoho State 1, top of dike impounded water analysis, 1983 from Hawaii Dept. of Land and Natural Resources (DLNR).
KS-1A	Geothermal Well, Kapoho State 1-A, top of dike impounded water analysis, 1985 from DLNR.
KS-2	Geothermal Well, Kapoho State 2, top of dike impounded water analysis, 1984 from DLNR.
HGP-A	Geothermal Well, HGP-A, analysis from 2270' from Kroopnick et al (1978).
GTW-IIIa	Geothermal hole, 7 Jan. '75 sample from WRRC, UH-M.
GTW-IIIb	Geothermal hole, 21 July '75 sample from WRRC, UH-M.
GTW-IIIc	Geothermal hole, (Thief), 21 July '75 sample from WRRC, UH-M.
9-6a	Kapoho hole, 6 Jan. '75 sample from WRRC, UH-M.
9-6b	Kapoho hole, 22 July '75 sample from WRRC, UH-M.
9-6c	Kapoho hole, analysis from Cox and Thomas (1979).
GTW-IV	Geothermal hole, 21 June '61 sample from Hawaii Department of Health (HDOH).

a - Total Fe
b - Not Available

Table 2 (Cont'd.)

WELL

Parameter	9a	9b	9c	9d	A	9-9a	9-9b	9-9c	9-9d	9-9e	9-7a	9-7b
Temp(°F)	77.9	71.8	N.A.	N.A.	99.5	126	N.A.	N.A.	128	N.A.	83.3	69.4
pH	7.8	7.1	7.7	7.2	7.35	7.02	7.45	6.92	7.1	6.92	7.68	7.05
Na	85.8	86.5	97	139	216	2105	2890	2935	2695	3090	89.6	78.8
K	6.6	6.2	14	25	10.8	109	149	155	129		5.2	5.0
Ca	42.4	23.2	47.7	14	13.4	66.8	117	182	122	182	5.3	5.9
Mg	37	25.7	26.5	17	15	210	293	324	267	324	6.6	5.6
Cl	16.9	95.7	125	331	281	3811	5120	5850	6887	5850	132.2	120
SO_4	20	22.7	5.5	65.4	69.2	471	598	681	583	681	37.6	38.6
HCO_3	372	328	283	61	132	144	128	262	173	N.A.	N.A.	N.A.
SiO_2	53.6	N.A.	44	70.5	24.1	100.7	N.A.	59	83.2	59	44.5	N.A.
P	0.233	0.268	N.A.	N.A.	<0.002	0.006	0.013	N.A.	N.A.	N.A.	0.056	0.194
Fe^a	N.A.	N.A.	N.A.	0.2	N.A.	N.A.	N.A.	N.A.	3.16	3.16	N.A.	N.A.
TDS	635	588	643	723	762	7018	9295	10450	10949	11700	359	291
Cl/Mg	0.46	3.72	4.7	19.47	18.73	18.15	17.47	18.06	25.79	18.06	20.0	21.43

9a Kapoho Shaft, 6 Jan. '75 sample from WRRC, UH-M.
9b Kapoho Shaft, 21 July '75 sample from WRRC, UH-M.
9c Kapoho Shaft, 15 March '68 sample from Hawaii Board of Water Supply.
9d Kapoho Shaft, sample from DLNR.
A Well Allison, 7 Jan. '75 sample from WRRC, UH-M.
9-9a Malama-Ki Well, 7 Jan. '75 sample from WRRC, UH-M.
9-9b Malama-Ki Well, 22 July '75 sample from WRRC, UH-M.
9-9c Malama-Ki Well, 6 Sept. '62, sample from USGS.
9-9d Malama-Ki Well, Cox and Thomas (1979).
9-9e Malama-Ki Well, 28 Sept. '62 from DLNR.
9-7a Kalapana Station, 6 Jan. '75 sample from WRRC, UH-M.
9-7b Kalapana Station, unspecified date for sample from WRRC, UH-M.

JLI038

a – Total Fe
b – Not Available

Table 3. Water chemistry analyses for fresh water drinking wells on the Island of Oahu. Data taken from Young (1981).

WELL

Parameter	Kaimuki	Wilder	Beretania	Kalihi
Temp (°F)	<85*	<85*	<85*	<85*
pH	8.2	8.3	8.3	8.15
Na	55	52	39	42
K	2.3	3.1	3.7	2.5
Ca	9.0	4.5	10	14
Mg	11	6.2	11	14
Cl	79	56	62	80
SO_4	14	9.5	9.7	13
HCO_3	76	79	73	71
SiO_2	41	34	37	44
P	NA	NA	NA	NA
Fe	.02	.02	.02	.02
TDS	322	249	248	283
Cl/Mg	7.2	9.0	5.6	5.7

*Parameter not reported by Young (1981). It is assumed given the type of well and location.

Table 4. Listing of wells in the LERZ relative to fresh or geothermal water types, see text for explanation.

WELLS CONTAINING GEOTHERMAL WATERS

TDS > 2000 mg/l	Temperature > 100°F	Cl/Mg > 15
KS-1	KS-1	KS-1
KS-1A	KS-1A	KS-1A
KS-2	KS-2	KS-2
HGP-A	HGP-A	HGP-A
GTW-IIIa, b, and c	GTW-IIIa, b, and c	GTW-IIIa, b, and c
9-9a, b, c, d, and e	A	9-6c,
	9-9a, and d	9d
	GTW-IV	A
		9-9a, b, c, d and e
		9-7a and b

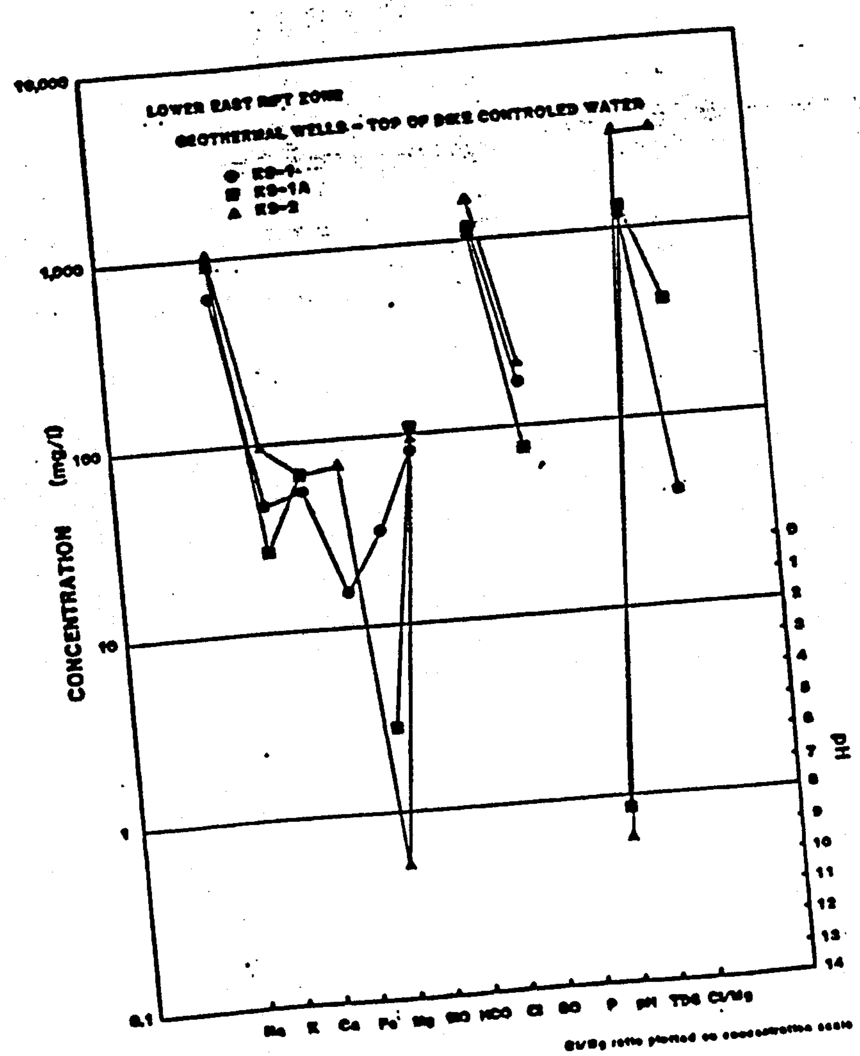
WELLS CONTAINING FRESH WATERS

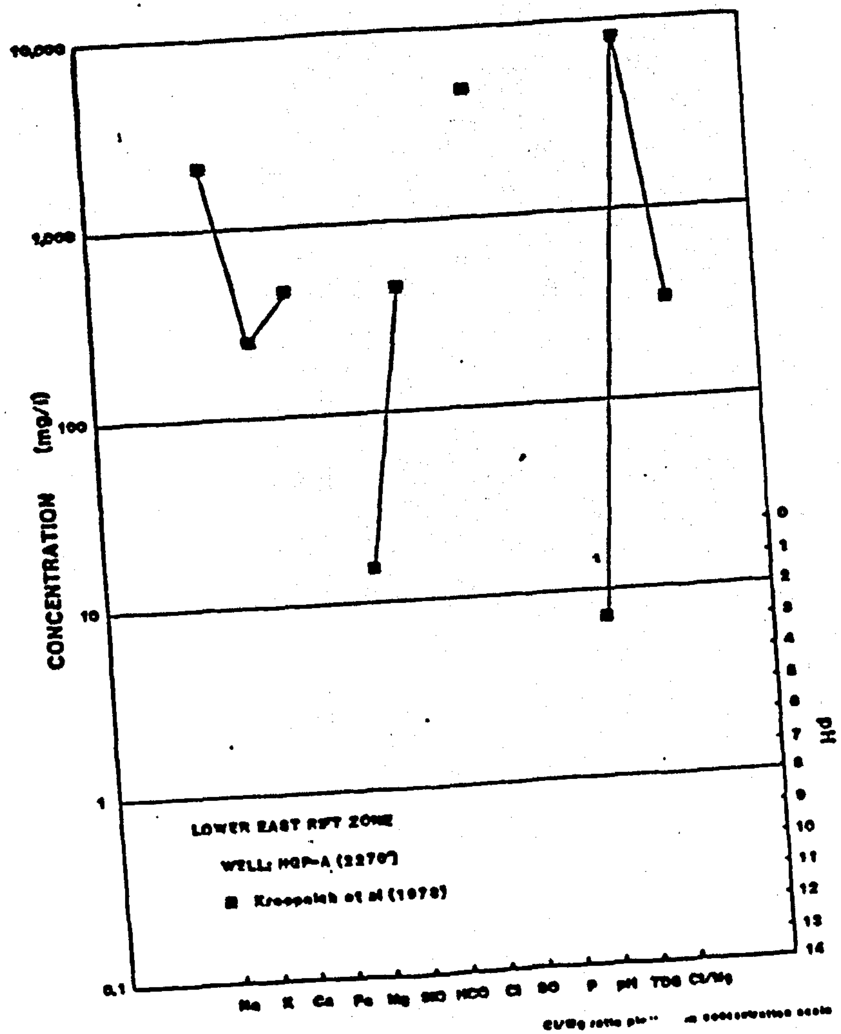
TDS < 2000 mg/l	Temperature < 100°F	Cl/Mg < 15
PSa, PSb	PSa, PSb	PSa, PSb
PVTW	PVTW	PVTW
9-6a, b, c	9-6a, b, c	9-6a and b
GTW-IV	GTW-IV	9a and b
9a, b, c, and d	9-7a and b	9a, b and c
A	Kaimuki	Kaimuki
9-7a and b	Wilder	Wilder
Kaimuki	Beretania	Beretania
Wilder	Kalihi	Kalihi
Beretania		
Kalihi		

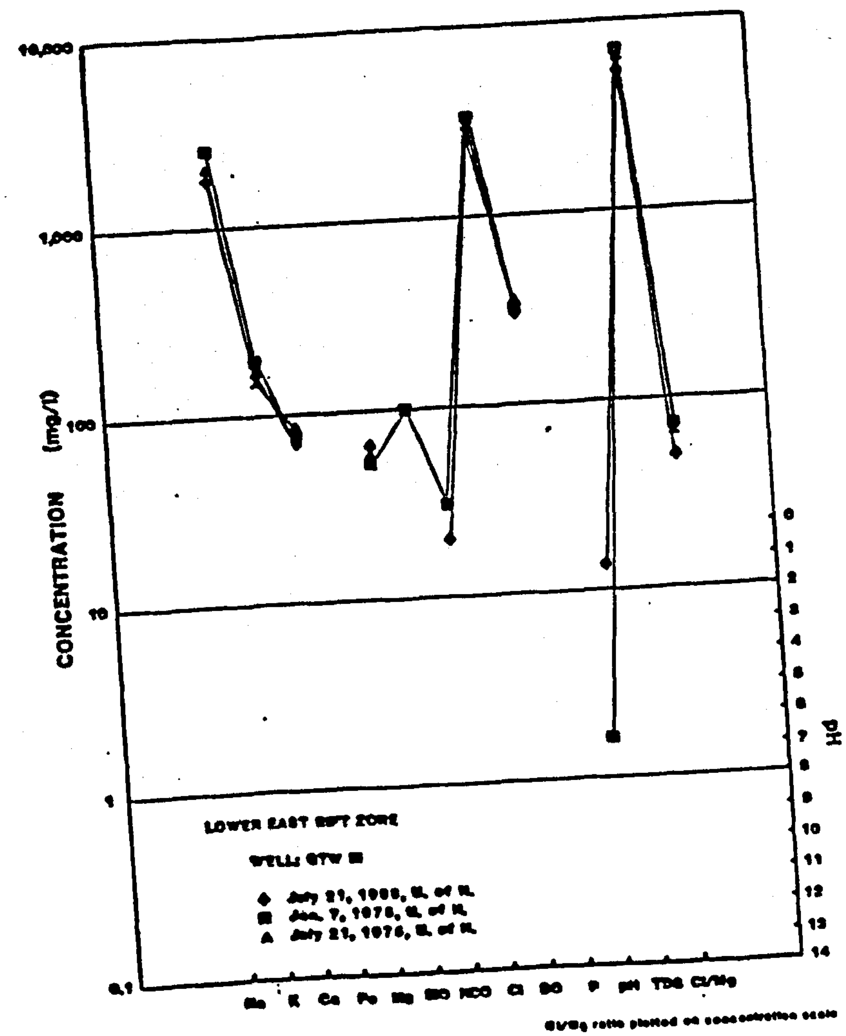
Table 5. Characterization of fresh, geothermal and mixed waters in the LERZ. See text for explanation.

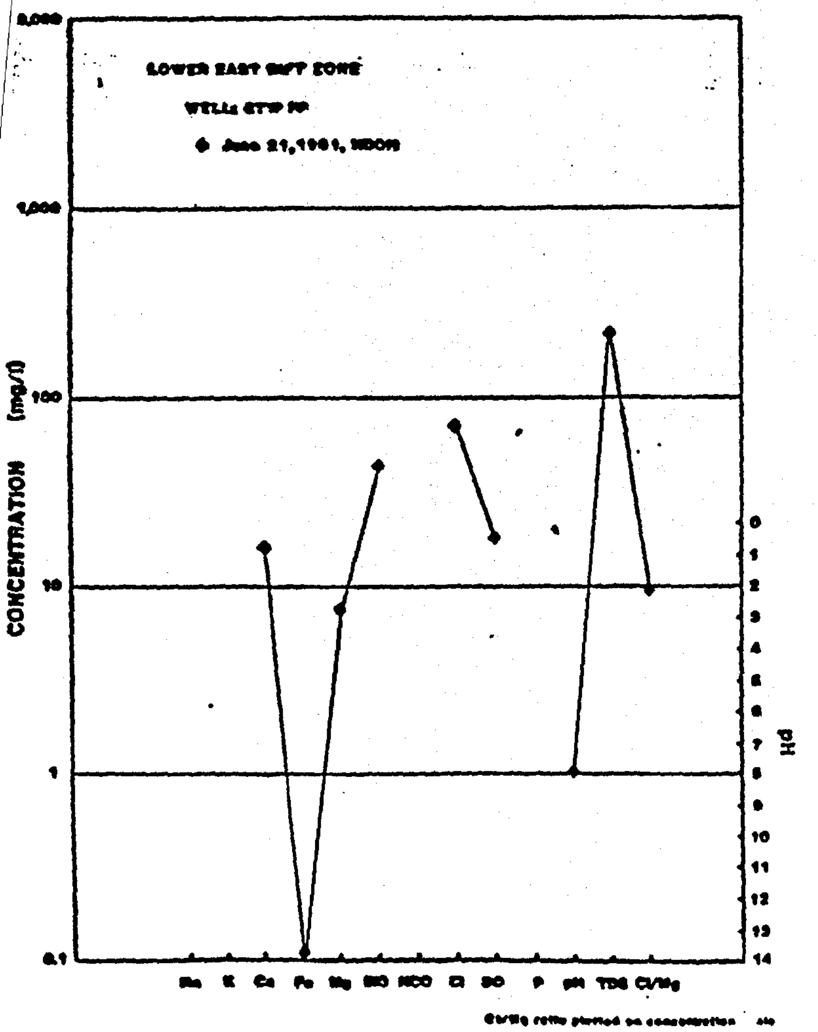
WELL	WATER TYPE
PSa, PSb	Fresh
PVTW	Fresh
KS-1	Geothermal
KS-1A	Geothermal
KS-2	Geothermal
HGP-A	Geothermal
GTW-IIIa, b and c	Geothermal
9-6a, b and c	Mixed
GTW-IV	Mixed
9a, b, c, and d	Mixed
A	Geothermal
9-9a, b, c, d, and e	Geothermal
9-7a and b	Fresh
Kaimuki	Fresh
Wilder	Fresh
Beretania	Fresh
Kalihi	Fresh

ix A: Individual Schoeller Diagrams for Wells in the Lower East Rift Zone

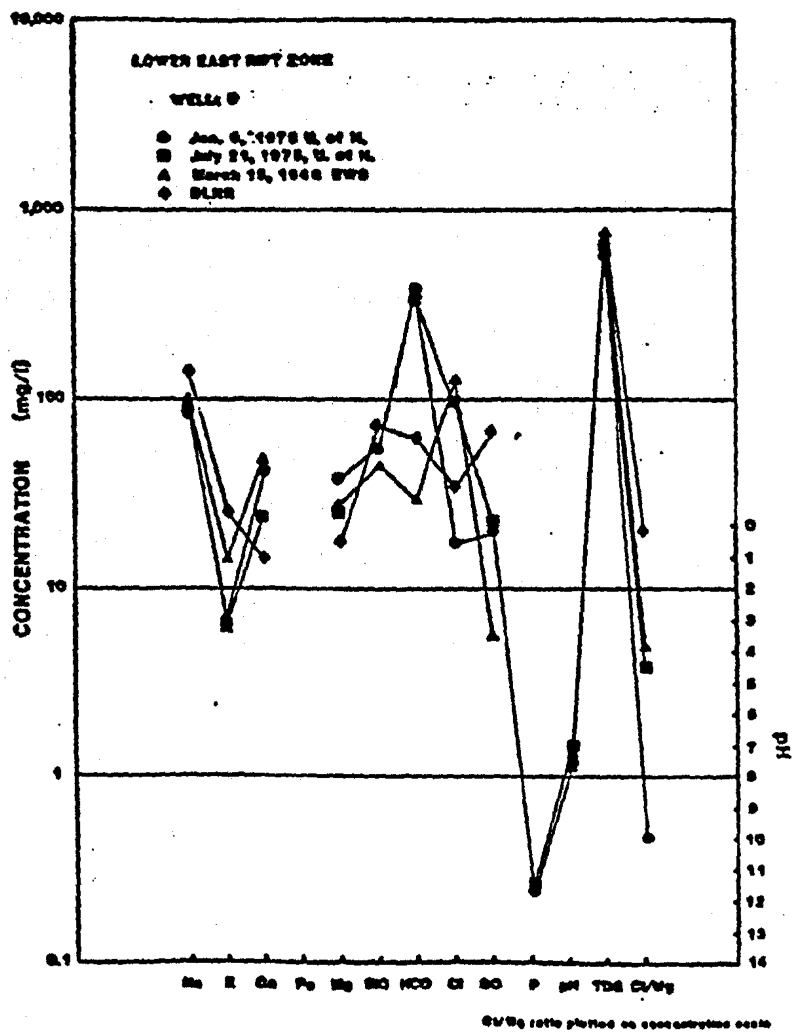



CONCENTRATION (mg/l)
10,000
1,000
100
10
1
0.1
pH
LOWER EAST RIFT ZONE
WELL: HGP-A (2270')
Kroopnick et al (1978)
Na K Ca Fe Mg SIO HCO Cl SO P pH TDS Cl/Mg

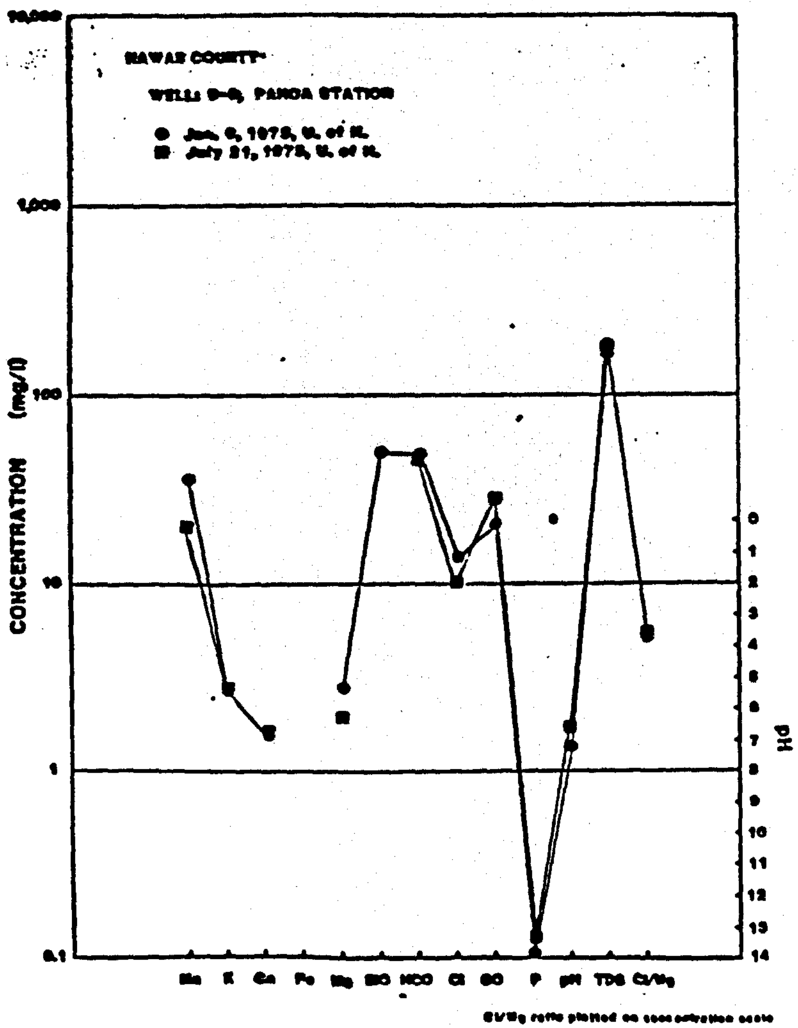

CONCENTRATION (mg/l)
10,000
1,000
100
10
1
0.1
pH
LOWER EAST RIFT ZONE
WELL: GTW III
Na K Ca Fe Mg SIO HCO Cl SO P pH TDS Cl/Mg
Cl/Mg ratio plotted on concentration scale



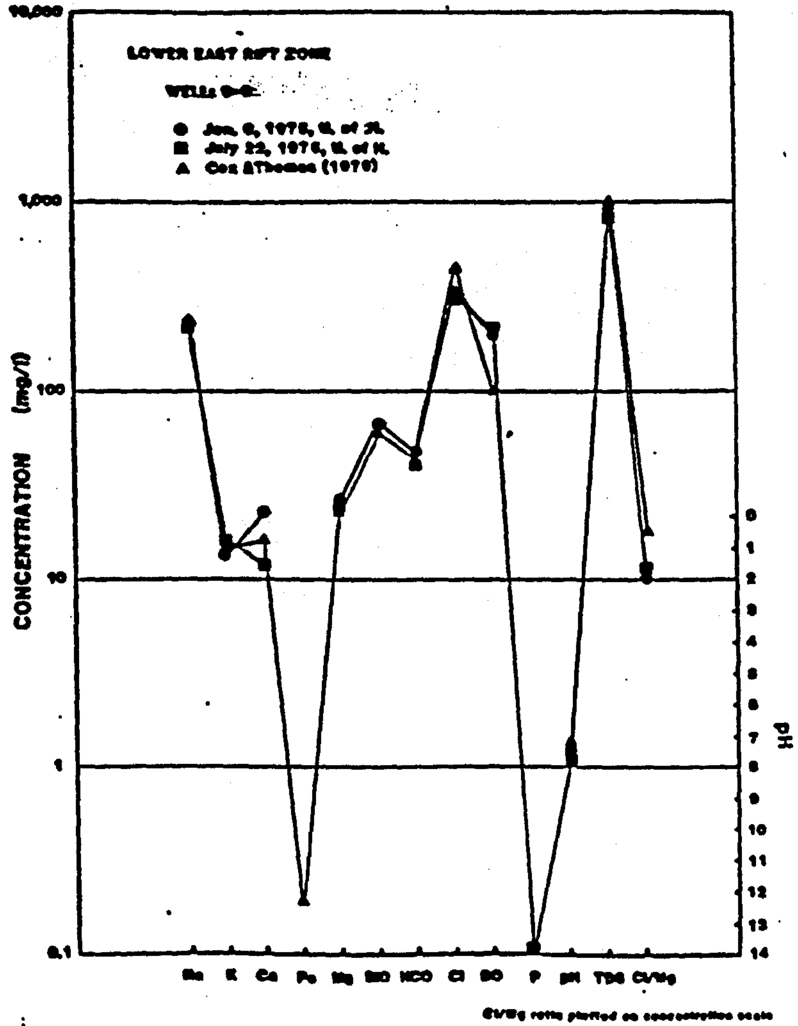
LOWER EAST RIFT ZONE
CONCENTRATION (mg/l)
pH
Na K Ca Fe Mg SiO HCO Cl SO P pH TDS Cl/Mg



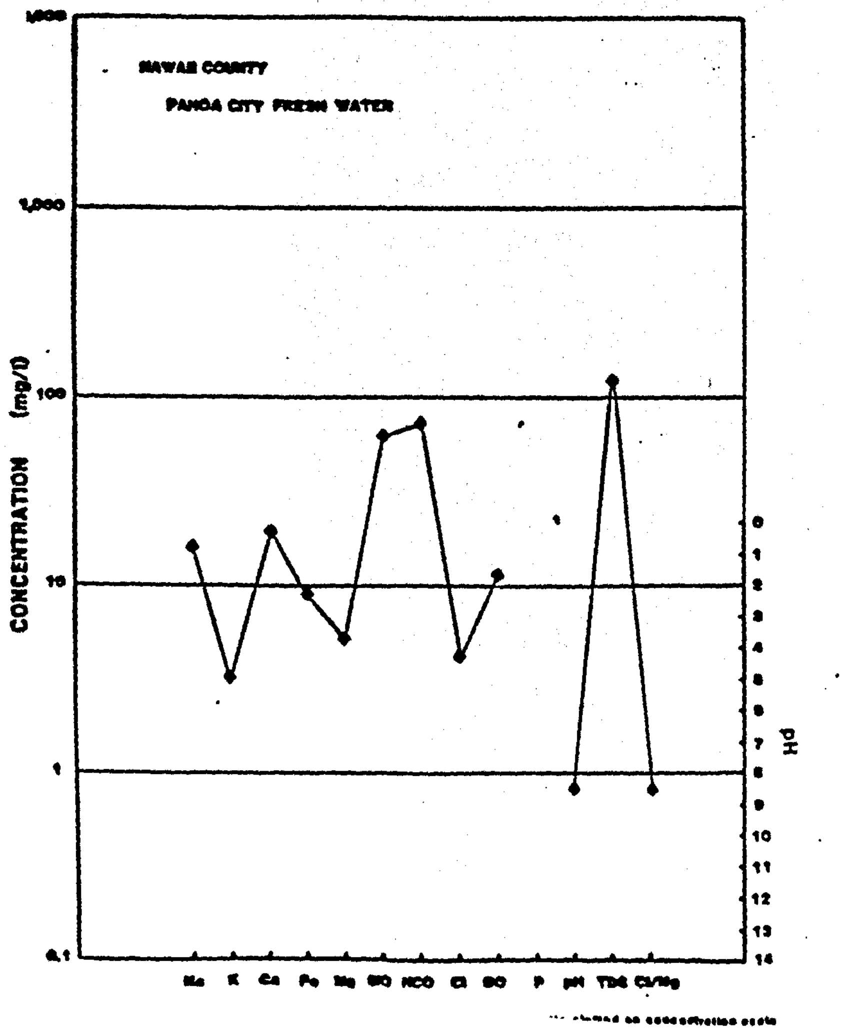
LOWER EAST RIFT ZONE
10,000
1,000
100
10
1
0.1
CONCENTRATION (mg/l)
pH
Na K Ca Fe Mg SiO HCO Cl SO P pH TDS Cl/Mg
Cl/Mg ratio plotted on concentration scale

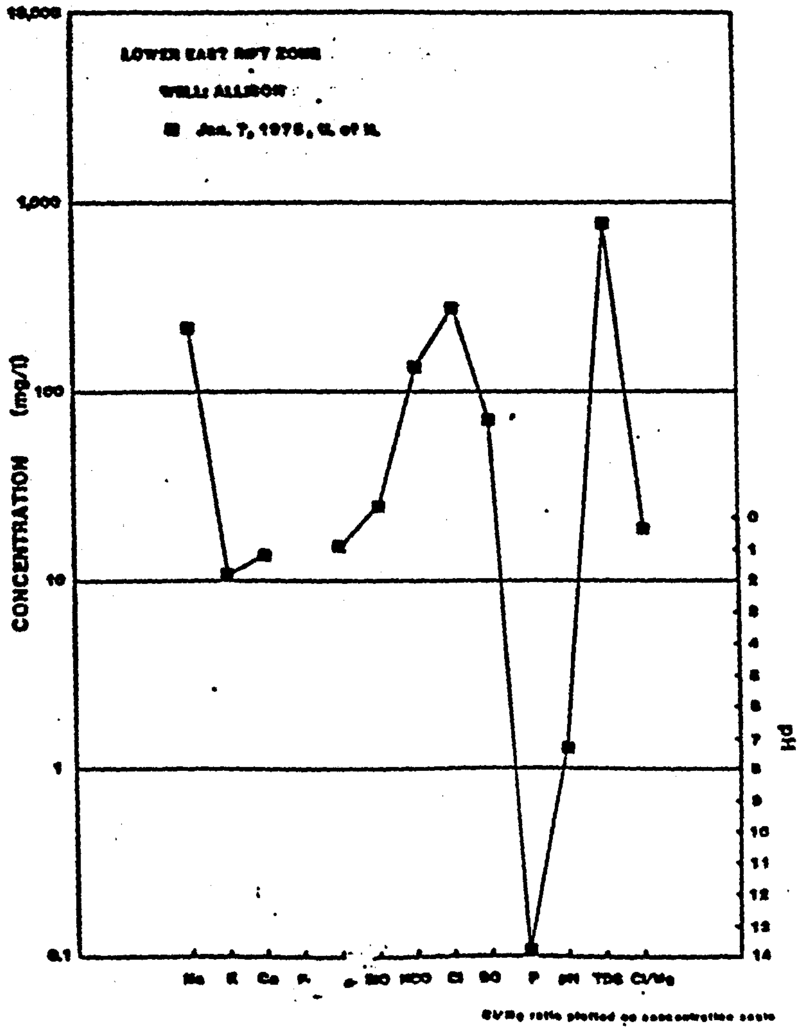


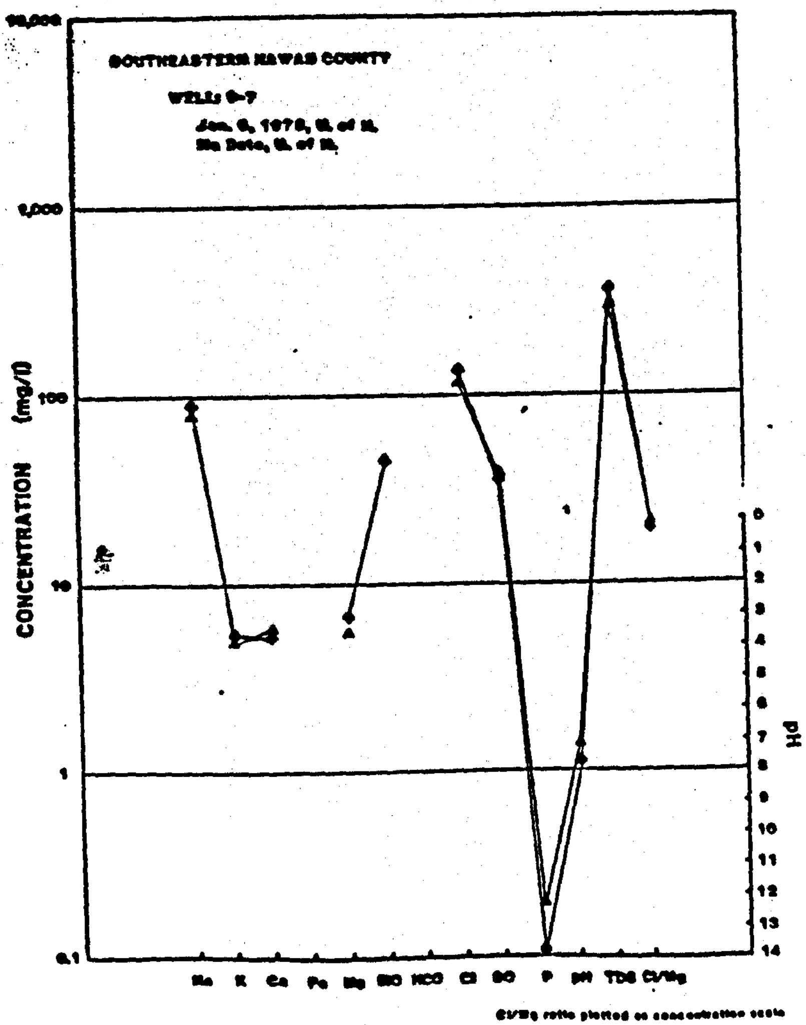
CONCENTRATION (mg/l)
pH
10,000
1,000
100
10
1
0.1
TDS

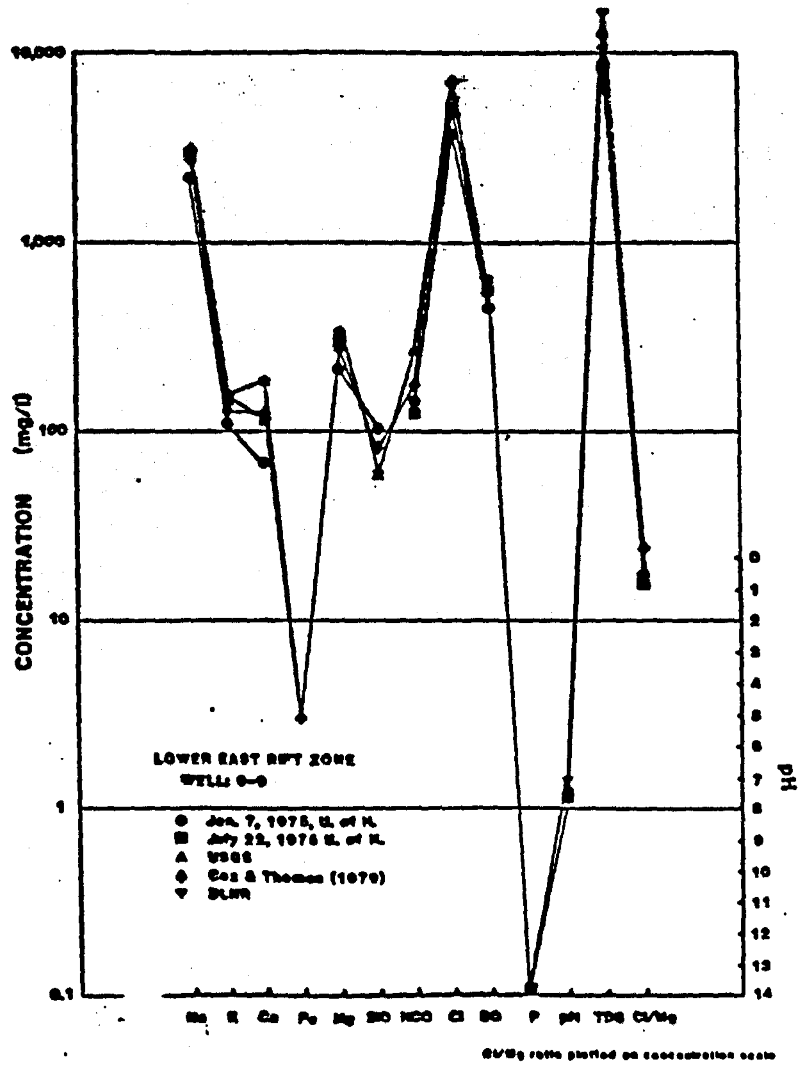


LOWER EAST RIFT ZONE
CONCENTRATION (mg/l)
pH
10,000
1,000
100
10
1
0.1
TDS


HAWAII COUNTY
PAHOA CITY FRESH WATER
CONCENTRATION (mg/l)
pH


LOWER EAST RIFT ZONE
CONCENTRATION (mg/l)
pH


CONCENTRATION (mg/l)
pH
1,000
100
10
1
0.1
TDS


CONCENTRATION (mg/l)
pH
10,000
1,000
100
10
1
0.1
LOWER EAST RIFT ZONE
USGS
TDS